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Differentiation

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13. Abstract (Maximum 200 Words) (abstract should contain no proprietary or confidential information) Cell adhesive events play essential roles in the pathophysiology of breast cancer. Two important biological phenomena have been shown to depend upon integrins. The differentiation of breast cancer cells depends upon the expression of $\alpha 2 \beta 1$ integrin on the cell surface. The creation of distant metastasis is supported by the association of breast cancer cells with platelets. This association depends on the interaction between the activated $\alpha \nu \beta 3$ integrin on the breast cancer cell surface with the activated $\alpha \text{IIb} \beta 3$ integrin on the platelet surface. Thus, it is reasonable to assume that modulation of the function of those integrins may lead to the differentiation of poorly-differentiated breast cancer or the prevention of distant metastasis to other organs. To attain this goal, it is imperative to understand the precise mechanisms of integrin-ligand interaction. In this project I identified the ligand contact surfaces of $\alpha 2 \beta 1$ and $\alpha \text{IIb} \beta 3$ integrins. The ligand contact site in $\alpha 2 \beta 1$ is composed of several discontinuous amino acid residues surrounding the MIDAS in the $\alpha 2$ I domain. The $\alpha \text{IIb} \beta 3$ ligand binding interface is located on the outer edge and side of the propeller centering on $\beta$ -sheet 3 of the $\alpha \text{IIb} \beta$ -propeller domain. These findings may form the basis for developing therapeutics for breast cancer.				
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## Table of Contents

Cover.....	1
SF 298.....	2
Table of Contents.....	3
Introduction.....	4
Body.....	5
Key Research Accomplishments.....	8
Reportable Outcomes.....	8
Conclusions.....	8
References.....	9
Appendices.....	10

## 4. INTRODUCTION

Cell adhesive events play essential roles in many important physiological and pathological aspects in breast cancer, such as its differentiation (1, 2, 3) and metastatic properties. Loss of  $\alpha 2\beta 1$  integrin expression is associated with the aggressive phenotype of breast cancer in patients (4). Artificial manipulation of  $\alpha 2\beta 1$  integrin expression in breast cancer cell lines leads to the change in phenotype (5, 6).

These lines of evidence suggest that  $\alpha 2\beta 1$  integrin-ligand interaction is crucial for breast cancer differentiation. These results suggest that modulation of integrin, particularly  $\alpha 2\beta 1$ , could be an important therapeutic target for breast cancer. Integrins also play critical roles in the pathogenesis of distant metastasis through interaction with vascular endothelial cells and their extracellular matrices. In general, the prerequisite step in creating hematogenous metastasis is for the tumor cells to withstand the shear force in the blood stream and arrest in the blood vessels. It has been shown that platelet thrombus provides melanoma cells stable anchorage that withstand the shear force. This stable interaction between platelets and melanoma cells was dependent on  $\alpha \text{IIb}\beta 3$  on platelets and  $\alpha \text{V}\beta 3$  on melanoma cells (7). In breast cancer, the  $\alpha \text{V}\beta 3$  integrin characterizes the metastatic phenotype, since it is up-regulated in invasive tumors and distant metastases. However, it is not yet known why this integrin is associated with the metastatic phenotype. Recently, Felding-Habermann *et al.* have shown that breast cancer cell arrest during blood flow is supported by activated  $\alpha \text{V}\beta 3$  through its interaction with platelets (8). Thus, it is reasonable to assume that breast cancer cells metastasize to distant organs utilizing platelets as anchorage. It is therefore important to characterize the interaction between tumor cells and platelets. Previous reports suggest that  $\alpha \text{IIb}\beta 3$  on platelets, other unknown molecules on the tumor cell side, and bridging adhesive proteins are involved in this interaction (7, 9). Therefore the  $\alpha \text{IIb}\beta 3$ -adhesive protein interaction could be a key target for creating the therapeutic modalities to prevent hematogenous metastasis. The purpose of this study is to elucidate the binding mechanisms of pathophysiologically relevant integrins in breast cancer, namely  $\alpha 2\beta 1$  and  $\beta 3$  integrins.

## 5. BODY

### 5.a. Collagen contact site in $\alpha 2\beta 1$

#### 5.a.1. Discontinuous multiple amino acid residues in the I domain are required for collagen binding

The MIDAS (metal ion-dependent adhesion site) face, the putative ligand binding face, of the  $\alpha 2$  I domain is composed of four discontinuous loop structures. The  $\beta A$ - $\alpha 1$ ,  $\alpha 3$ - $\alpha 4$ , and  $\beta D$ - $\alpha 5$  loops contain amino acid residues that compose the MIDAS motif, which is critical for divalent cation coordination (10, 11). These amino acid residues are relatively well conserved among different I domains. On the contrary, the amino acid sequences of the  $\beta E$ - $\alpha 6$  loop are variable. Notably, there are five amino acid insertions within this loop in collagen-binding  $\alpha 1$ ,  $\alpha 2$ ,  $\alpha 10$ , and  $\alpha 11$  integrin I domains. The crystal structure of  $\alpha 2$  I domain revealed that these inserted residues constitute an extra C-helix within the  $\beta E$ - $\alpha 6$  loop (12). This C-helix creates a groove on top of the MIDAS face in which a collagen triple helix is predicted to dock. Therefore the C-helix was predicted to be the major determinant of collagen binding. Based on the crystal structure of  $\alpha 2$  I domain, I replaced loops surrounding the MIDAS motif with the homologous loops of  $\alpha L$  and examined the effect on ligand binding (see the 1999 annual report and manuscript 1 for details). The L  $\beta A$ - $\alpha 1$  and L  $\alpha 3$ - $\alpha 4$  mutants almost completely abolished collagen adhesion even though the MIDAS motif is maintained. The L  $\beta D$ - $\alpha 5$  mutant partially affected collagen adhesion. On the other hand, the del  $\alpha C$  mutant, which is missing most of the  $\beta E$ - $\alpha 6$  loop including the C-helix, did not have any impact on collagen adhesion even though  $\alpha C$  is predicted to have a collagen contact site (12). These results suggest that the collagen contact sites are localized in the  $\beta A$ - $\alpha 1$ ,  $\alpha 3$ - $\alpha 4$ , and  $\beta D$ - $\alpha 5$  loops of the  $\alpha 2$  I domain, and that the C-helix does not contain any energetically important collagen contact sites. To further characterize the collagen-contact face, I introduced multiple point mutations into the residues within those critical loops. Consistent with the results from loop-swapping mutagenesis, I found that Ser-153, Ile-156, and Tyr-157 in  $\beta A$ - $\alpha 1$ ; Gln-215 and Gly-218 in  $\alpha 3$ - $\alpha 4$ ; and Gly-255 in  $\beta D$ - $\alpha 5$ , in addition to the previously reported Asp-151, Thr-221 and Asp-254, are critical for collagen binding. In addition, mutation of Asn-154, Ser-155, Asp-219 and His-258 had a mild blocking effect on collagen binding when collagen type I was immobilized at 2  $\mu\text{g/ml}$ . Consistent with the data obtained from the del  $\alpha C$  mutant, mutations in the amino acid residues in the  $\beta E$ - $\alpha 6$  loop did not affect collagen binding at all (see manuscript 1 for detail). These results suggest that the energetically important collagen contact sites are localized in relatively conserved sequences surrounding the MIDAS motif.

#### 5.a.2. $\alpha 2$ I domain/collagen binding model

In collaboration with Dr. Liddington, we created an  $\alpha 2$  I domain/collagen docking model based on the mutagenesis data. In the crystal structure, Asp-151, Ser-153, Ser-155, Thr-221 and Asp-254 are involved in the coordination of the cation. Ile-156 is totally buried in the molecule. Mutations of Gln-215, Gly-218 and Gly-255 are either buried or likely to disrupt the MIDAS motif. In contrast, Asn-154, Tyr-156, Asp-219, and His-258 are totally exposed on the surface of the molecule, suggesting that these residues make direct contact with collagen. Recently, a short synthetic triple-helical peptide, representing residues 502-516 of the collagen type I  $\alpha$  chain, has been shown to support purified  $\alpha$  $\beta$  and recombinant  $\alpha$  I-domain binding (13). The Glu and Arg residues in the GER triplet were found to be essential for recognition by the  $\alpha$  I-

domain. In the current model, Asn-154, Tyr-157, Asp-219, and His-258 make direct contact with collagen, and the arginine from the GER motif makes a salt bridge to Glu-256 (see manuscript 1 for detail). In addition, Tyr-285 from the C-helix also makes direct contact with collagen. However, current mutagenesis data suggests that this is not energetically important.

The actual crystal structure of a complex between the  $\alpha 2$  I domain and a collagen triple helical peptide has been published. The crystal structure has a striking similarity to the docking model we created, except that the  $\alpha C$  helix undergoes extensive conformational change and moves away from the collagen triple helix (14). This result completely agrees with our mutagenesis data since we could not find any critical residues for collagen binding in the  $\alpha C$  helix, contrary to the original assumption that the  $\alpha C$  helix contains a critical collagen binding site (12). All the amino acid residues essential for collagen binding in our study make direct contact with collagen in the crystal structure. These results indicate that we can accurately predict the ligand binding sites in integrins using mutagenesis data.

## **5.b. Ligand binding interface of $\alpha I Ib$**

### **5.b.1. Swapping mutagenesis of $\alpha I Ib$**

Previous studies on breast cancer and other cancer cells suggest that cancer cells use  $\alpha V \beta 3$  or unknown receptors on their surface to bind to  $\alpha I Ib \beta 3$  on platelets via bridging molecules for anchorage (7, 8, 9). So far, it is not clear what adhesive proteins bridge between the tumor cells and activated platelets under flow conditions. However, several reports suggest that tumor cells may utilize fibrinogen or vWF (vonWillebrand factor) at least in part as a bridging molecule (7, 9, 15). The  $\alpha I Ib \beta 3$  integrin is a prototypic integrin that is also known as Glycoprotein IIb-IIIa (GPIIb-IIIa). The ligand binding specificity of  $\alpha I Ib \beta 3$  is rather promiscuous and it also binds to proteins such as fibronectin, vitronectin, and thrombospondin in an RGD-dependent manner, as well as fibrinogen and vWF (16). Since  $\alpha I Ib \beta 3$  is the common molecule utilized for anchorage by a variety of cancer cells, we sought to determine the ligand binding site in  $\alpha I Ib \beta 3$ .

To localize the ligand binding site in  $\alpha I Ib \beta 3$ , I used the same strategy for localizing the collagen contact site in  $\alpha 2 \beta 1$ . The first step is to create a swapping mutant of  $\alpha I Ib$  in which a particular amino acid sequence is replaced by the homologous sequence from a different integrin alpha subunit that has different ligand binding specificity. Since the three-dimensional structure of integrin alpha subunit is not yet known, except for the I domain of the I domain-containing integrins, it is difficult to determine what surface-exposed segment can be swapped without affecting the gross conformation or surface expression. I first aligned the amino acid sequences of  $\alpha I Ib$  with  $\alpha 4$  and  $\alpha 5$ , which do not bind to fibrinogen or vWF. Based on the secondary structure prediction of  $\alpha 4$ , predicted loops between the  $\beta$ -strands were chosen for swapping mutagenesis (see the 2000 annual report for details).

### **5.b.2. Eight discontinuous predicted loops in $\alpha I Ib$ are essential for fibrinogen binding to $\alpha I Ib \beta 3$ integrin.**

Fibrinogen binding to cells expressing mutant  $\alpha I Ib \beta 3$  were examined as previously described (17, 18). Out of 27 swapping mutants we created, W2A, W2C, W3A, W3C, W3D, W4A, W4C, and W5A mutants did not bind fibrinogen, even though they all bound to the activating mAb PT25-2 and showed comparable  $\alpha I Ib \beta 3$  expression levels. The W5D mutant did not bind to fibrinogen either in this system. However, it failed to bind to PT25-2. The W5D mutant had an intact

fibrinogen binding site, since it bound to fibrinogen using other activation methods (see the 2000 annual report for details). The binding of the ligand-mimetic antibody PAC-1 to those mutants was also examined. Similar to the fibrinogen binding results, W2A, W2C, W3A, W3C, W3D, W4A, and W5A mutants showed significantly reduced binding to PAC-1 upon activation with PT25-2. On the contrary, the W4C mutant, which showed impaired binding to fibrinogen, exhibited PAC-1 binding comparable to wt (Fig. 1).

#### 5.b.3. Multiple discontinuous amino acid residues are essential for fibrinogen binding.

To minimize the effect on the overall conformation of  $\alpha$ IIb $\beta$ 3, point mutations were introduced into the regions that affect fibrinogen binding when swapped. We introduced alanine mutations into individual amino acid residues within the critical W2A, W2C, W3A, W3C, W3D, W4A, W4C, and W5A regions. Fig. 2 shows the fibrinogen binding to CHO cells expressing those mutants. The Ala mutation of Asp-74, Leu-84, and Phe-87 in W2A; Trp-110, His-112, and Trp-113 in W2C; Arg-147, Tyr-155, Phe-160, Asp-163, and Arg-165 in W3A; Tyr-189, Tyr-190, Phe-191, and Gly-193 in W3C; Ile-203, Phe-204, and Tyr-207 in W3D; Ser-222, Asp-224, Phe-231, and Asp-232 in W4A; Leu-264 in W4C; and Gln-284 and Met-285 in W5A almost completely blocked fibrinogen binding when replaced by alanine. The other mutations did not significantly affect fibrinogen binding. These point mutations affected mAb binding to various degrees (data not shown). These results indicate that specific residues essential for fibrinogen binding can be localized within the regions identified by swapping mutagenesis. Some of those residues most likely compose the fibrinogen contact site.

#### 5.b.4. Molecular modeling of $\alpha$ IIb

In collaboration with Dr. Springer, we generated an  $\alpha$ IIb  $\beta$ -propeller model based on the alignment of  $\alpha$ IIb with the  $\beta$ -propeller domain of the beta subunit of heterotrimeric G protein (Fig. 3). The loops of each  $\beta$ -sheet or W are named after the  $\beta$ -sheets they connect. The 4-1 and 2-3 loops correspond to positions A and C, respectively, and are located very close to each other in the upper face of the model. The 1-2 and 3-4 loops correspond to positions B and D, respectively, and are located in the lower face of the model. Loop swaps that did or did not eliminate binding are shown as red and green, respectively, and individual alanine substitutions are similarly color coded and shown as spheres. The model reveals that the amino acid residues critical for ligand binding that were identified in this study are clustered in the outer edge of  $\beta$ -sheet 2-5. It is interesting that among these residues, Ile-203, Phe-204, and Tyr-207 in the 3-4 loop of W3 are located on the side of the  $\beta$ -propeller. The model predicts that the outer  $\beta$ 4 strand between the critical 3-4 loop of W3 and the 4-1 loop of W4 is surface-exposed (shown as magenta in Fig. 3), and thus may constitute part of the ligand-binding interface. Consistent with this prediction, swapping mutation of the entire  $\beta$ 4 strand ( $\beta$ 4W3), and Ala mutation of Leu-212 and Leu-213 within the strand, disrupted ligand binding (Fig.4). The outer  $\beta$ 4 strand between the 3-4 loop of W5 and the 4-1 loop of W6, which is not essential for ligand binding, is also surface-exposed in the model. In contrast, swapping mutation of the strand did not block ligand binding at all (data not shown). These results suggest that the ligand-binding interface may lie not only on the top face, but also on the side of the  $\beta$ -propeller toroid, centering on  $\beta$ -sheet 3. In fact, the sides contribute to ligand binding in many  $\beta$ -propellers (19, 20, 21). These side residues are clustered near those in the top of the  $\beta$ -propeller, and all may contribute to a common ligand-binding surface. Alternatively, they may have an indirect effect on the  $\beta$ -propeller or on a



neighboring domain.

Consistent with the proposed critical function of these residues in ligand binding, most of these surface-exposed residues are well conserved among human (22), rat (23), and mouse  $\alpha$ IIb (18, 24), except that Leu-84 is replaced with Phe in rat and mouse  $\alpha$ IIb, Phe-205 is replaced with Ile in mouse and rat  $\alpha$ IIb, and Tyr-190 and Ser-222 are replaced with homologous Phe and Thr, respectively, in mouse and rat sequences.

## 6. KEY RESEARCH ACCOMPLISHMENTS

- a. Identification of the collagen contact site in the I domain of  $\alpha$ 2 $\beta$ 1 integrin.
- b. Generation of a collagen/ $\alpha$ 2 I domain docking model.
- c. Mapping of a monoclonal antibody epitope in  $\alpha$ IIb
- d. Identification of the fibrinogen binding interface in  $\alpha$ IIb $\beta$ 3 integrin.
- e. Generation of the  $\beta$ -propeller model of the  $\alpha$ IIb subunit.

## 7. REPORTABLE OUTCOMES

### 7.a. Manuscripts

1. Kamata T, Liddington RC, Takada Y. Interaction between collagen and the alpha(2) I-domain of integrin alpha(2)beta(1): Critical role of conserved residues in the metal ion-dependent adhesion site (MIDAS) region. J Biol Chem 274:32108-11, 1999.
2. Puzon-McLaughlin W, Kamata T, Takada Y. Multiple discontinuous ligand-mimetic antibody binding sites define a ligand binding pocket in integrin alpha(IIb)beta(3). J Biol Chem 275:7795-802, 2000.

### 7.b. Presentations

Kamata T, Liddington RC, Takada Y. Identification of collagen contact site in alpha(2)beta(1) integrin: Critical role of conserved residues in the metal-dependent adhesion site (MIDAS) region. Department of Defense Breast Cancer Research Program Era of Hope Meeting 2000.

### 7.c. Development of cell lines

Numerous stable CHO cell lines expressing mutant alpha(2) integrin were established.

## 8. CONCLUSIONS

The collagen contact site in  $\alpha$ 2 $\beta$ 1 integrin is composed of the amino acid residues Asn-154, Tyr-157, Asp-219, and His-258, which surround the MIDAS motif of the  $\alpha$ 2 I domain. These residues make direct contact with the collagen triple-helical peptide in the collagen/ $\alpha$ 2 I domain complex crystal structure.

Nine discontinuous short segments in  $\alpha$ IIb are essential for  $\alpha$ IIb $\beta$ 3 binding to fibrinogen. Among the amino acid residues within those segments, Asp-74, Leu-84, Phe-87, Trp-110, His-112, Trp-113, Arg-147, Tyr-155, Phe-160, Asp-163, Arg-165, Tyr-189, Tyr-190, Phe-191, Gly-



193, Ile-203, Phe-204, Tyr-207, Leu-212, Leu-213, Ser-222, Asp-224, Phe-231, Asp-232, Leu-264, Gln-284, and Met-285 eliminated fibrinogen binding when mutated. These residues are clustered on the outer edge and side of the propeller centering on  $\beta$ -sheet 3 in the  $\beta$ -propeller model.

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## 10. APPENDICES

### 10.a. Bibliography of all publications and meeting abstracts

1. Kamata T, Liddington RC, Takada Y. Interaction between collagen and the alpha(2) I-domain of integrin alpha(2)beta(1): Critical role of conserved residues in the metal ion-dependent adhesion site (MIDAS) region. J Biol Chem 274:32108-11, 1999.
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3. Kamata T, Liddington RC, Takada Y. Identification of collagen contact site in alpha(2)beta(1) integrin: Critical role of conserved residues in the metal ion-dependent adhesion site (MIDAS) region. Department of Defense Breast Cancer Research Program Era of Hope Meeting 2000.

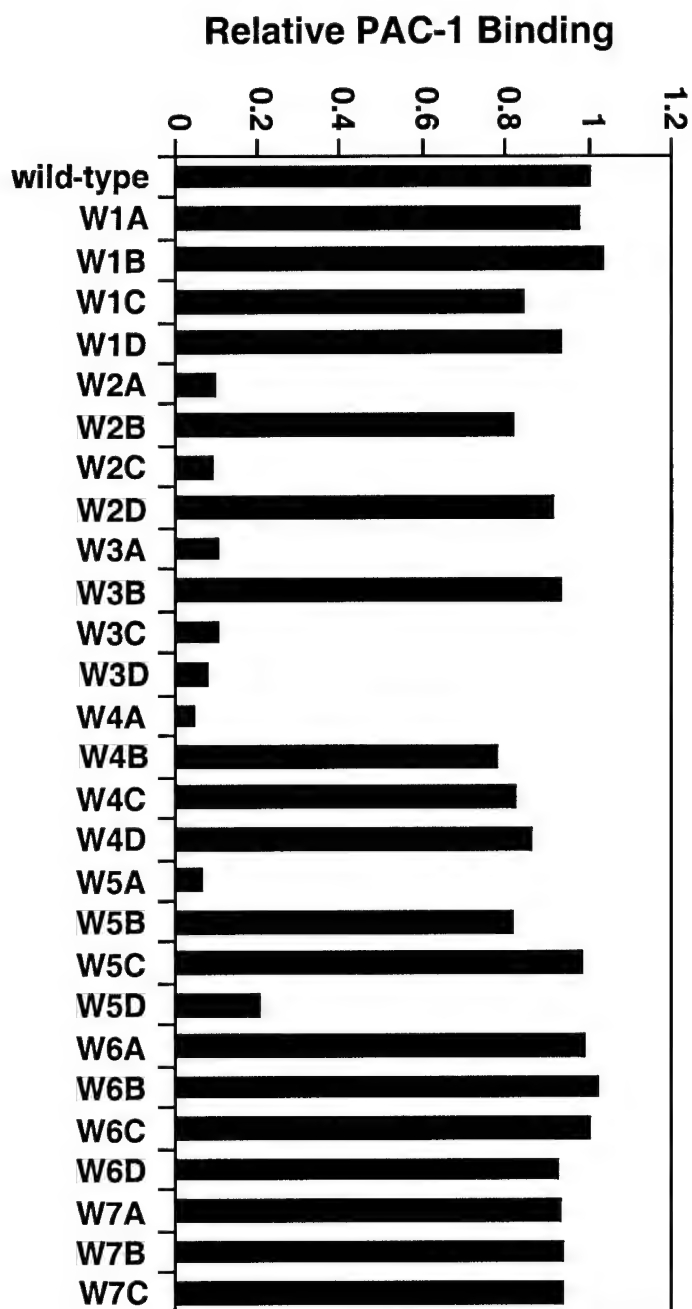
### 10.b. List of personnel receiving pay from the research effort

Tetsuji Kamata

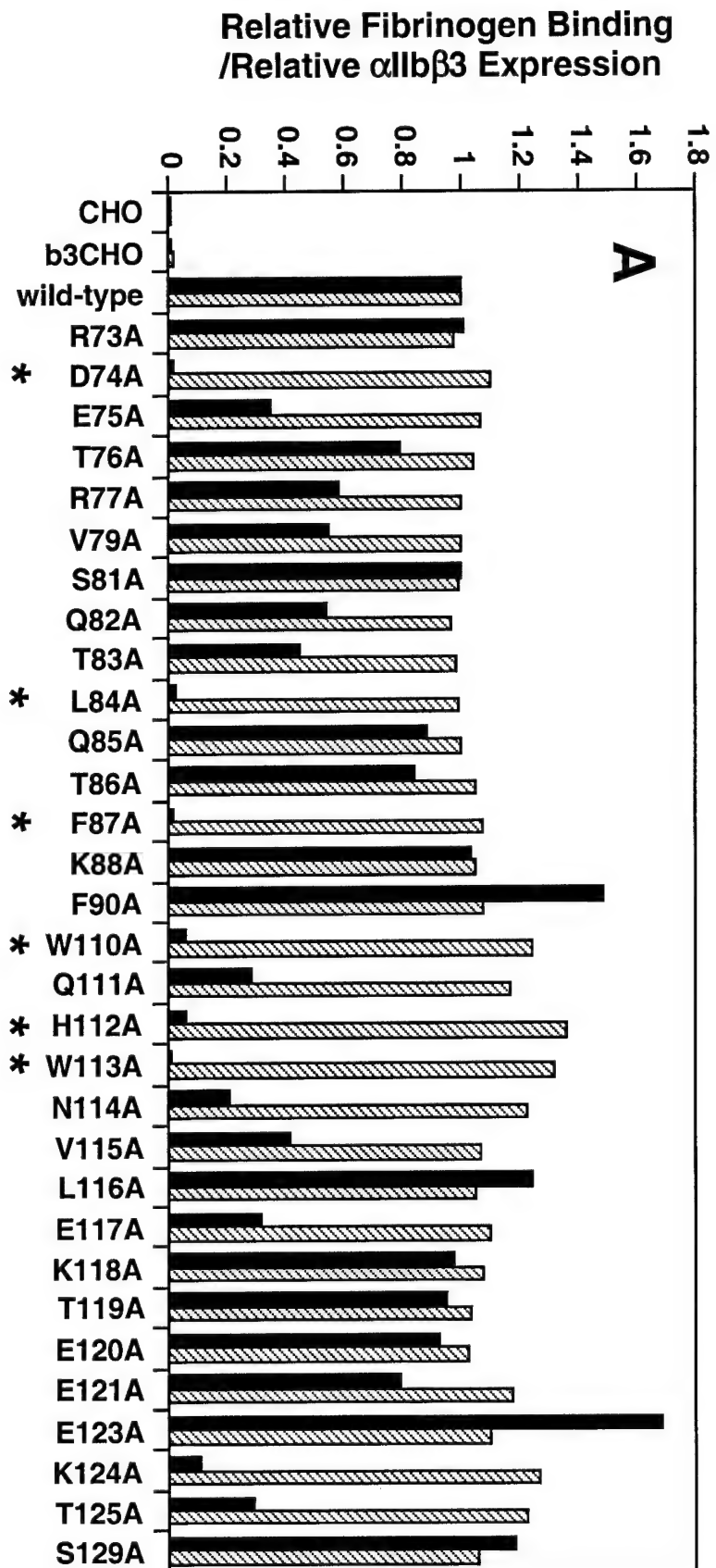
### 10.c. Figures 1 to 4

### 10.d. Journal Articles

1. Kamata T, Liddington RC, Takada Y. Interaction between collagen and the alpha(2) I-domain of integrin alpha(2)beta(1): Critical role of conserved residues in the metal ion-dependent adhesion site (MIDAS) region. J Biol Chem 274:32108-11, 1999.
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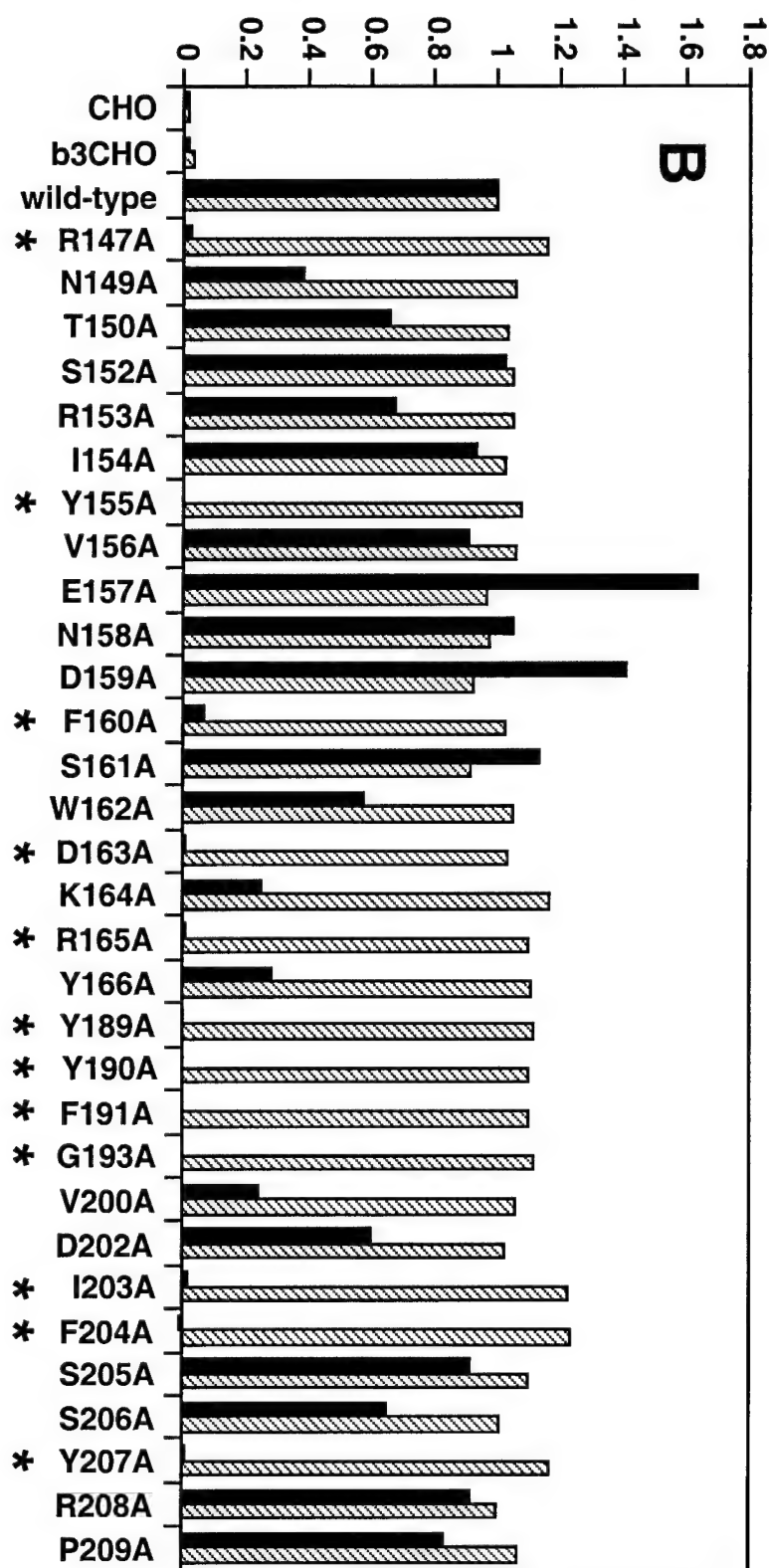


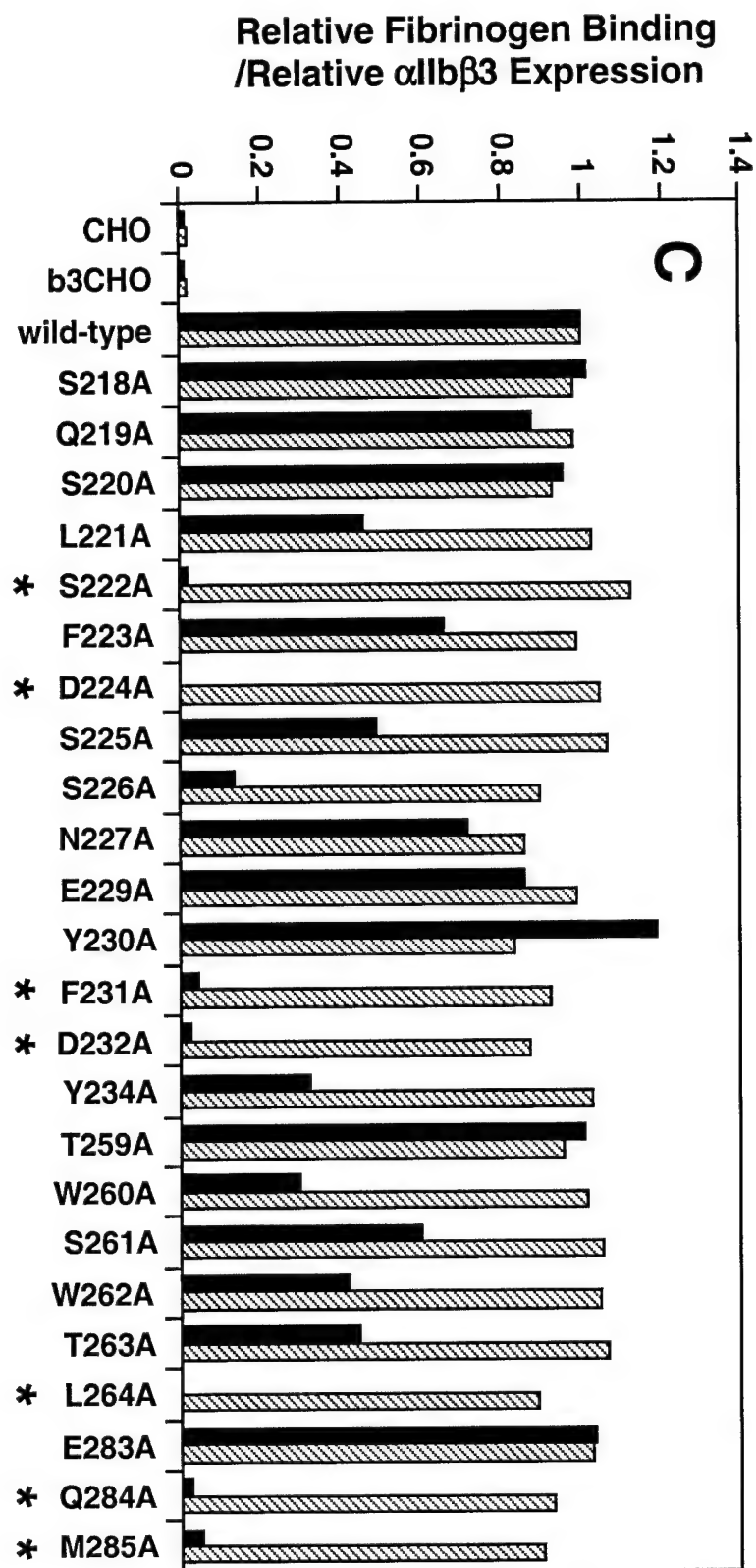
**Fig. 1. PAC-1 binding to swapping mutants.**  $\beta$ 3-CHO cells transiently expressing  $\alpha$ IIb mutants were stained either with PAC-1 in the presence of PT25-2 or with PL98DF6. Bound IgM (PAC-1) and IgG (PL98DF6) was detected with FITC-conjugated anti-mouse IgM or anti-mouse IgG, respectively. Percent PAC-1 binding was first normalized with  $\alpha$ IIb $\beta$ 3 expression with PL98DF6 (anti- $\alpha$ IIb). The normalized PAC-1 binding was divided by the normalized PAC-1 binding to cells expressing wt  $\alpha$ IIb $\beta$ 3 to obtain relative PAC-1 binding.

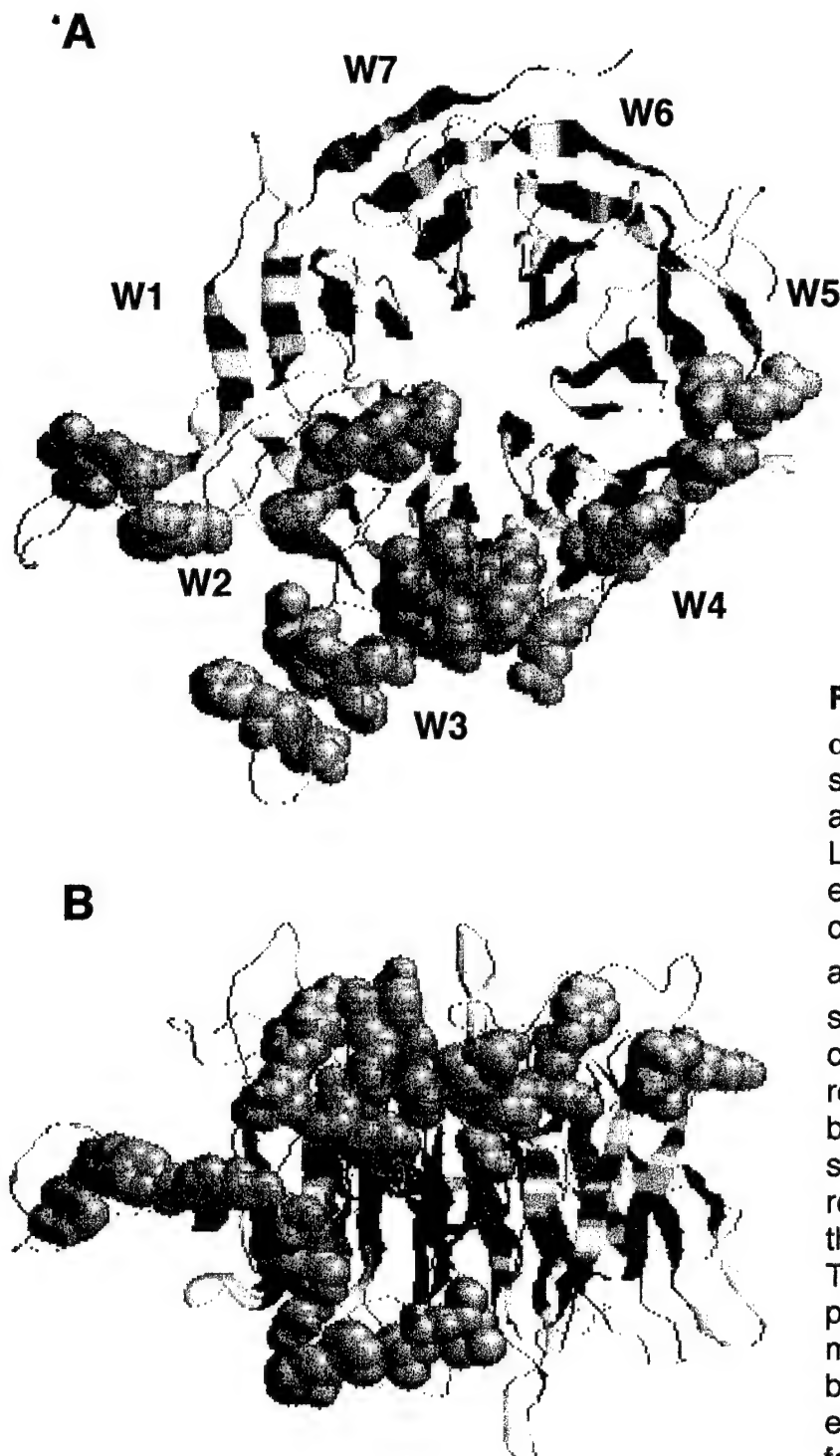


**Fig. 2. Fibrinogen binding to  $\alpha$ IIb point mutants.** Individual amino acid residues within the predicted  $\beta$ -sheet 2 (A),  $\beta$ -sheet 3 (B),  $\beta$ -sheet 4 and 5 (C) were mutated to Ala by site-directed mutagenesis. Mutant  $\alpha$ IIb cDNAs were transiently expressed in  $\beta$ 3-CHO. Cells were first stained with PL98DF6 followed by PE-conjugated anti-mouse IgG. After washing, cells were incubated with FITC-labeled fibrinogen in the presence of PT25-2 or normal mouse IgG. Fibrinogen binding to a gated subset of cells expressing  $\alpha$ IIb $\beta$ 3 at a high level (PE-positive) was analyzed in flow cytometry. Relative fibrinogen binding (solid bar) and relative  $\alpha$ IIb $\beta$ 3 expression (hatched bar) were calculated as described in previous report. Fibrinogen binding to parent CHO and  $\beta$ 3-CHO are included as controls. Mutants that exhibit fibrinogen binding less than 5 % of wild-type fibrinogen binding are marked with asterisks.

# Relative Fibrinogen Binding /Relative $\alpha$ IIb $\beta$ 3 Expression

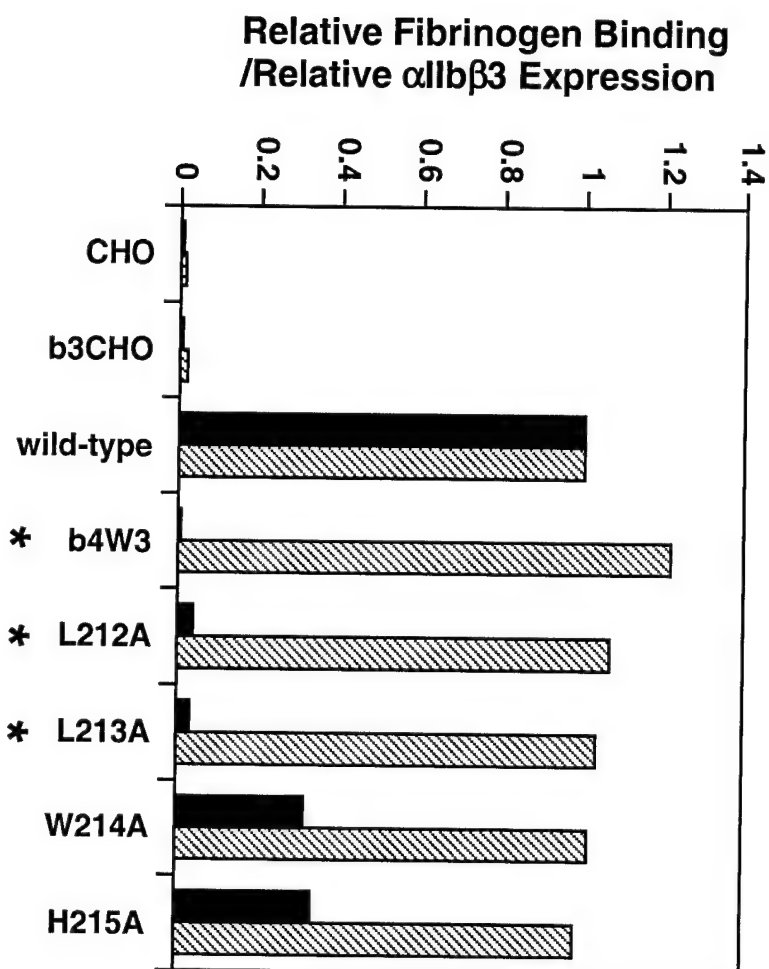






**Fig. 3. The  $\beta$ -propeller model of  $\alpha_{IIb}$ .** The seven four-stranded  $\beta$ -sheets (W) are arranged in a torus around a 7-fold pseudosymmetry axis. Loop swaps that did or did not eliminate fibrinogen binding are color coded as red and green, respectively and shown as ribbons. The outer  $\beta 4$  strand in  $\beta$ -sheet 3 (W3) is color coded as magenta. Amino acid residues that blocked fibrinogen binding when mutated to alanine are shown as spheres. The other residues that were not examined in this study are shown as blue ribbons. Top (A) and side (B) views of the propeller are shown. Note that mutations that eliminated fibrinogen binding are clustered in the top outer edge and side, but not in the bottom face of the propeller.





**Fig. 4. Effect of mutations of  $\beta$ 4-strand residues in  $\beta$ -sheet-3 on fibrinogen binding.** Amino acid residues in the predicted  $\beta$ 4 strand in  $\beta$ -sheet-3 of  $\alpha$ IIb was swapped with homologous residues from  $\alpha$ 5. Individual amino acid residues within this region was mutated to Ala. The resulting  $\beta$ 4W3 chimera and Ala mutants were transiently expressed in  $\beta$ 3-CHO cells. Fibrinogen binding to cells expressing wt or mutant  $\alpha$ IIb $\beta$ 3 was examined as described in previous report. Relative fibrinogen binding (solid bar) and relative  $\alpha$ IIb $\beta$ 3 expression (hatched bar) are shown. Mutants that exhibit fibrinogen binding less than 5 % of wild-type fibrinogen binding are marked with asterisks.

# Interaction between Collagen and the $\alpha_2$ I-domain of Integrin $\alpha_2\beta_1$

## CRITICAL ROLE OF CONSERVED RESIDUES IN THE METAL ION-DEPENDENT ADHESION SITE (MIDAS) REGION\*

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**A docking model of the  $\alpha_2$  I-domain and collagen has been proposed based on their crystal structures (Emsley, J., King, S., Bergelson, J., and Liddington, R. C. (1997) *J. Biol. Chem.* 272, 28512–28517). In this model, several amino acid residues in the I-domain make direct contact with collagen (Asn-154, Asp-219, Leu-220, Glu-256, His-258, Tyr-285, Asn-289, Leu-291, Asn-295, and Lys-298), and the protruding C-helix of  $\alpha_2$  (residues 284–288) determines ligand specificity. Because most of the proposed critical residues are not conserved, different I-domains are predicted to bind to collagen differently. We found that deleting the entire C-helix or mutating the predicted critical residues had no effect on collagen binding to whole  $\alpha_2\beta_1$ , with the exception that mutating Asn-154, Asp-219, and His-258 had a moderate effect. We performed further studies and found that mutating the conserved surface-exposed residues in the metal ion-dependent adhesion site (MIDAS) (Tyr-157 and Gln-215) significantly blocks collagen binding. We have revised the docking model based on the mutagenesis data. In the revised model, conserved Tyr-157 makes contact with collagen in addition to the previously proposed Asn-154, Asp-219, His-258, and Tyr-285 residues. These results suggest that the collagen-binding I-domains (e.g.  $\alpha_1$ ,  $\alpha_2$ , and  $\alpha_{10}$ ) bind to collagen in a similar fashion.**

Several integrin  $\alpha$  chains ( $\alpha_1$ ,  $\alpha_2$ ,  $\alpha_{10}$ ,  $\alpha_L$ ,  $\alpha_M$ ,  $\alpha_X$ ,  $\alpha_D$ , and  $\alpha_E$ ) have inserted I- or A- domains of about 200 amino acid residues (1–11). Integrins  $\alpha_1\beta_1$  (1),  $\alpha_2\beta_1$  (reviewed in Ref. 12), and  $\alpha_{10}\beta_1$  (4) have been shown to bind to collagen and/or laminin. Several function-blocking antibodies map to the I-domains of  $\alpha_2\beta_1$  (13) and  $\alpha_1\beta_1$  (14). The recombinant  $\alpha_2$  I-domain fragment binds to collagen (15, 16), and the recombinant  $\alpha_1$  I-domain fragment binds to collagen and laminin (17). Conserved Asp and Thr residues in the  $\alpha_2$  I-domain (Asp-151, Thr-221, and Asp-254) are critical for collagen binding (15). These lines of evidence suggest that the I-domain is critically involved in collagen binding.

The crystal structures of the I-domains of the integrin  $\alpha_M$  (18),  $\alpha_L$  (19), and  $\alpha_2$  (20) subunits, and the A1 (21, 22) and A3 (23, 24) domains of von Willebrand factor (vWf) have been

published. This domain adopts a classic “Rossmann” fold and consists of a hydrophobic  $\beta$ -sheet in the middle and amphipathic  $\alpha$ -helices on both sides. Interestingly, the integrin I-domain contains a  $Mg^{2+}/Mn^{2+}$  coordination site at its surface, which is not present in proteins with similar structures (e.g. the NAD binding domain of lactate dehydrogenase) or the vWf A1 and A3 domains (21–24). The Asp and Thr residues in  $\alpha_2$  that have been shown to be critical for ligand binding are involved in the coordination of a divalent cation in the crystal structure (20). The  $\alpha_2$  I-domain has a unique helix (the C-helix) protruding from the metal ion-dependent adhesion site (MIDAS) that creates a groove centered on the magnesium ion. Emsley *et al.* (20) proposed a model in which a collagen triple helix fits into the groove and a Glu side chain from collagen coordinates the metal ion. In this model, the C-helix is a major determinant for collagen binding. It was predicted that the following I-domain residues make direct contact with collagen: Asn-154 (the  $\beta_A$ - $\alpha_1$  turn), Asp-219 and Leu-220 (the  $\alpha_3$ - $\alpha_4$  turn), Glu-256 and His-258 (the  $\beta_D$ - $\alpha_5$  turn), and Tyr-285, Asn-289, Leu-291, Asn-295 and Lys-298 (the C-helix,  $\alpha_6$  and C- $\alpha_6$  turn). However, these residues are not well conserved among collagen-binding I-domains (e.g.  $\alpha_1$ ,  $\alpha_2$ , and  $\alpha_{10}$ ), suggesting that different I-domains interact with collagen in different manners. Here we show that mutation of the residues proposed to be critical for ligand binding or deletion of the entire C-helix did not significantly affect collagen binding to whole  $\alpha_2\beta_1$  expressed on mammalian cells except for Asn-154, Asp-219, and His-258. In contrast, mutating several conserved MIDAS residues including Tyr-157 significantly blocks collagen binding. We have revised the docking model based on the mutagenesis data. In the revised model, interaction between the  $\alpha_2$  I-domain and collagen is mediated by relatively conserved residues in the MIDAS on the N-terminal side of the I-domain. Thus, it is suggested that the collagen-binding I-domains (e.g.  $\alpha_1$ ,  $\alpha_2$ , and  $\alpha_{10}$ ) bind collagen in a similar fashion.

### EXPERIMENTAL PROCEDURES

**Monoclonal Antibodies**—HAS-3 and HAS-4 (25) are generous gifts from F. Watt (Imperial Cancer Research Fund, London, UK.)

**Adhesion of CHO Cells to Collagen**—Wells of 96-well microtiter plates (Immulon-2, Dynatech Labs., Inc., Chantilly, VA) were coated with type I collagen (2 or 10  $\mu$ g/ml) at 4 °C overnight. The other protein binding sites were blocked by incubating with 1% (w/v) bovine serum albumin (Calbiochem, CA) for 30 min at room temperature, and washing three times with phosphate-buffered saline (10 mM phosphate, 0.15 M NaCl, pH 7.4). Cells were harvested with 3.5 mM EDTA in phosphate-buffered saline and washed twice with Dulbecco's modified Eagle's medium.  $10^5$  cells (in 100  $\mu$ l of Dulbecco's modified Eagle's medium) were added to each well and incubated for 1 h at 37 °C. The wells were rinsed three times with phosphate-buffered saline to remove unbound cells. Bound cells were quantified by assaying endogenous phosphatase activity (26).

**Molecular Modeling**—A model of a collagen triple helix was constructed from the crystal structure (Ref. 27, Protein Data Bank code

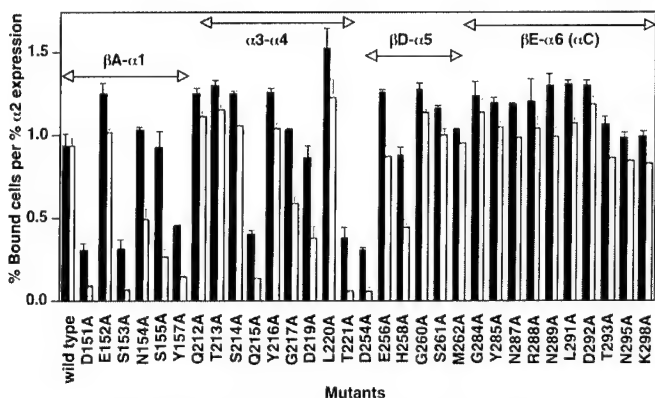
\* This work was supported by National Institute of Health Grants GM47157 and GM49899 (to Y. T.) and by United States Department of the Army Grant DAMD17-97-1-7105 (to T. K.). This is publication Number 12010-VB from The Scripps Research Institute. The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked “advertisement” in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

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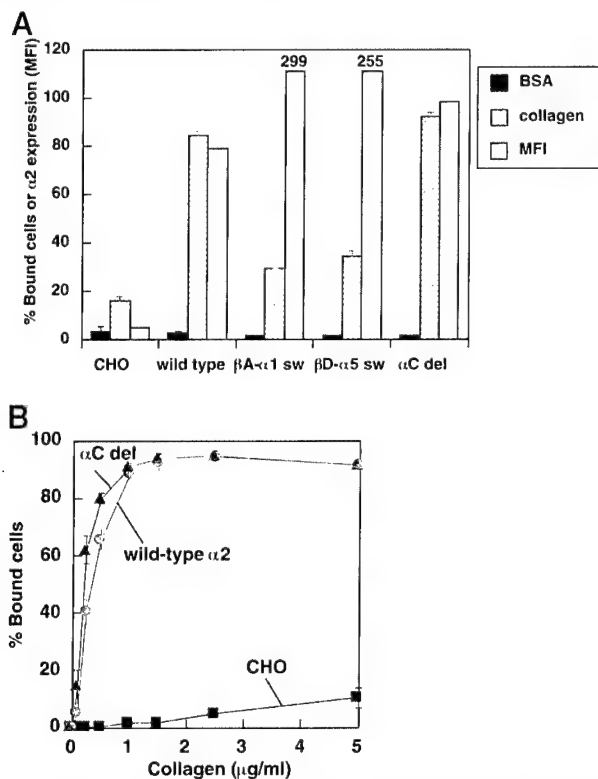
<sup>1</sup> The abbreviations used are: vWf, von Willebrand factor; MIDAS, metal ion-dependent adhesive site; CHO, Chinese hamster ovary.



These results suggest that collagen binding is mediated by relatively conserved MIDAS residues, which are located on the N-terminal side of the I-domain. Ser-153 and Ser-155 are involved in metal coordination, and mutating these residues would disrupt metal binding to the I-domain. Gln-215 is part of the MIDAS face and makes the main hydrogen bond to DXSXS loop. It is likely that mutating these residues blocks collagen

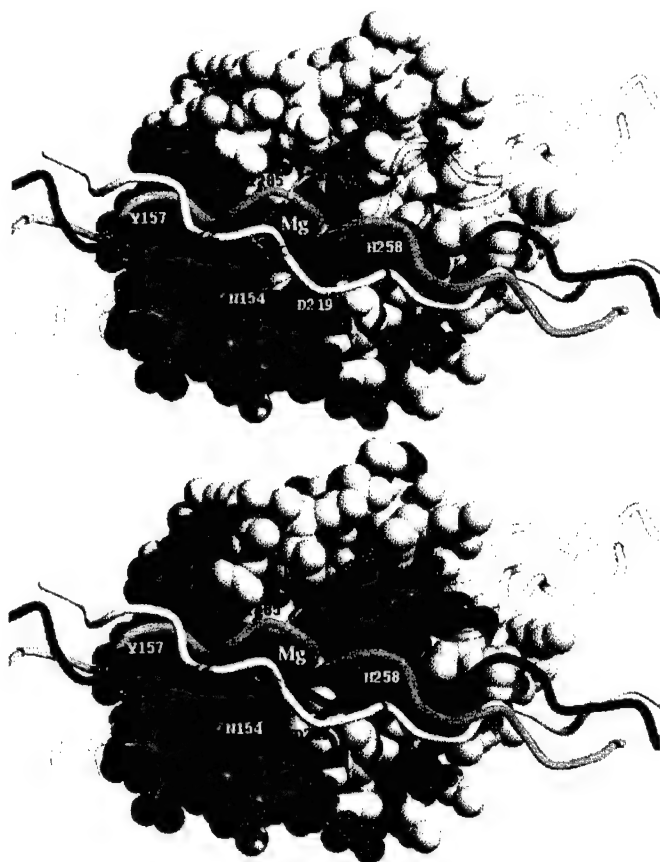


**FIG. 2. Effects of point mutations on collagen binding.** Cells stably expressing wild type or mutant  $\alpha_2$  were used to determine adhesion to collagen (at a 10 or 2  $\mu\text{g/ml}$  coating concentration, filled column and blank column, respectively). Data are presented as percent bound cells to collagen per percent human  $\alpha_2$  positive cells to normalize  $\alpha_2$  expression. Typically 40–60% of cells are positive after selection with G-418. Previously published function-negative mutations (D151A, T221A, and D254A) are included as negative controls. These results suggest that several relatively conserved residues in the  $\beta_A$ - $\alpha_1$ ,  $\alpha_3$ - $\alpha_4$ , and  $\beta_D$ - $\alpha_5$  loops are critical for collagen binding.



**FIG. 3. Effects of swapping/deletion mutations on collagen binding.** A, clonal CHO cells stably expressing wild type or mutant  $\alpha_2$  were incubated in the well coated with collagen type I or bovine serum albumin (negative control). After incubation at 37  $^{\circ}\text{C}$  for 1 h, non-adherent cells were removed and bound cells were determined by assaying endogenous phosphatase. Under the conditions used more than 80% of cells adhered to fibronectin as a positive control. Solid bar, BSA, bovine serum albumin; hatched bar, collagen; MFI, mean fluorescence intensity. B, adhesion to collagen of wild type and the  $\alpha_C$  deletion mutant  $\alpha_2$  was determined as a function of collagen coating concentrations. The data suggest that the adhesive function of the  $\alpha_C$  deletion mutant is comparable with that of wild type.

binding by disrupting metal binding to the I-domain. Asn-154, Asp-219, and His-258 have been predicted to make direct contact with collagen in the previous model (20), although the effects of mutating these residues are moderate. Tyr-157 is



**FIG. 4. A revised docking model of the  $\alpha_2$  I-domain and collagen.** All-atom representation of the  $\alpha_2$  I-domain, viewed looking down onto the MIDAS face. In the top panel, residues with mutations that reduce collagen binding are in red (surface-exposed) or pink (likely to disrupt MIDAS). Residues with mutations that have no effect on collagen binding are in cyan. The  $\text{Mg}^{2+}$  ion is shown as a gray ball. The new collagen model is shown as a colored triple helical coil (blue, green, and yellow) drawn through the  $\text{C}\alpha$  positions. The previous model (20) is shown as a transparent triple helical coil. Certain residues referred to under "Results and Discussion" are labeled. In the bottom panel, residues shown in red are invariant between  $\alpha_1$ ,  $\alpha_2$ , and  $\alpha_{10}$  I-domains.

totally exposed to the surface, and this residue may make direct contact with collagen. Tyr-157 has not been predicted to make direct contact with collagen. Mutating the other residues that are predicted to be critical for collagen binding in the proposed model (Leu-220, Glu-256, Tyr-285, Asn-289, Leu-291, Asn-295, and Lys-298) has no significant effect on collagen binding. Even deletion of the entire C-helix did not significantly affect collagen binding. These results support the role of the MIDAS motif in collagen binding because many of the mutants that affect collagen binding are predicted to disrupt the MIDAS motif. However, the present results are not fully consistent with the proposed model for collagen/ $\alpha_2$  I-domain binding (20).

We have modified the collagen/ $\alpha_2$  I-domain docking model based on the present mutagenesis data (Fig. 4). Recently, short synthetic triple-helical peptide corresponding to residues 502–516 of the collagen type I  $\alpha_1$  chain, has been shown to bind to purified  $\alpha_2\beta_1$  and recombinant  $\alpha_2$  I-domain (28). The Glu and Arg residues in the GER triplet were found to be essential for recognition by  $\alpha_2$  I-domain (28). In the current model, we first attached the glutamate side chain of the GER motif to the MIDAS  $\text{Mg}^{2+}$  ion. We then rotated the collagen to minimize the distance between the collagen and those surface-exposed residues implicated in collagen binding (His-258, Tyr-157, Asp-219, and Asn-154) while maintaining the 2-Å bond between the

glutamate oxygen and the  $Mg^{2+}$  ion and avoiding other close contacts ( $<2.5$  Å) with the protein. It was not initially possible to make favorable hydrogen bonds with all four side chains simultaneously, so the side chains were allowed to rotate about their  $C\alpha$ - $C\beta$  bonds to make plausible hydrogen bonds with the collagen backbone carbonyl oxygens and amide nitrogens. The collagen orientation was then refined to optimize the hydrogen bonding geometry. This procedure allowed all four I-domain side chains to make reasonable hydrogen bonds to the collagen. This model predicts that the side chain of Tyr-285, which projects from the C helix into the groove, makes unavoidable contact with the collagen and that further hydrogen bonds can be made between the Tyr hydroxyl and the collagen main chain. This revised model, which is rotated about 30 degrees from the previously published model, allows the arginine from the GER motif of the preceding strand to make a salt bridge to Glu-256. The previous model would not allow enough space for the arginine side chain without imposing unfavorable side chain torsion angles. Because mutation of Glu-256 does not significantly block collagen binding in the present study, this salt bridge might not be energetically important. The triple helical character of a symmetric collagen trimer generates three chemically distinct strands, which we call the leading, middle, and lagging strands. Attaching either the leading or middle strand glutamate to the  $Mg^{2+}$  ion leads to the same conclusions. Attaching the trailing strand makes a difference because there is no arginine from the preceding strand to form a salt-bridge to Glu-256. The alternative orientation with the collagen rotated by 180 degrees is much less favorable because the arginine of the GER motif would clash sterically with the I-domain. As pointed out in our previous model, an aspartic acid side chain in place of the GER glutamate would be too short to reach the  $Mg^{2+}$  ion without creating a large number of steric clashes. Because Asn-154, Tyr-157, His-258 are conserved in other collagen-binding integrin I-domains ( $\alpha_1$  and  $\alpha_{10}$ ), it is reasonable to assume that these residues are also involved in collagen binding in these integrins (Fig. 4). This model is consistent with the observation that tyrosine and arginine are enriched in hot spots of binding energy in the protein-protein interface (33).

In the present model, the highly conserved D151 and D254 residues in the  $\alpha_2$  I-domain are buried underneath the  $Mg^{2+}$  ion and cannot contact collagen directly. We have reported that mutating these residues only partially affects collagen binding to the recombinant  $\alpha_2$  I-domain fragment (13, 15). Also, Bienkowska *et al.* (23) reported that mutating the corresponding residues in the recombinant fragment of the vWf A3 domain does not affect collagen binding. However, the same mutation in the whole  $\alpha_2$  molecule completely blocks collagen binding to  $\alpha_2\beta_1$  (13, 15). It is possible that cation coordination through these residues is critical for ligand binding in the I-domain of the integrin molecule but not in similar domains in non-integrin structures (e.g. vWf). Consistently, the cation-binding site is not present in the vWf A3 domain (23, 24). Further studies would be needed to clarify the role of the conserved Asp residues in integrin I-domains. Several other collagen-binding sites have been reported. A collagen binding surface on osteonectin has been mapped by mutagenesis: it consists of a flat surface 15 Å in diameter containing polar and apolar residues (34), a crucial arginine residue, and intriguingly a  $Ca^{2+}$  binding site that might be directly involved in collagen binding. Docking and mutagenesis of *Staphylococcus aureus* adhesin identified another crucial arginine and a narrow groove as the binding site for collagen (35). The collagen binding surface on vWF-A3 has not been mapped but the structurally analogous surface lacks the charged residues found in the integrin I-domains (23,

24). Further studies will be required to determine whether there are any common collagen binding mechanisms.

While this paper was under review, the crystal structure of a GER-containing collagen peptide/ $\alpha_2$  I domain complex has been solved.<sup>2</sup> Preliminary analysis reveals that the structure is very similar to the revised model described here. Thus, the orientation and location of the collagen is as predicted, with Glu residues from the collagen coordinating directly to the metal ion. In addition, there is an unexpected change in the C helix so that it no longer touches the collagen, in agreement with the mutagenesis results.

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<sup>2</sup> J. Emsley, C. G. Knight, M. J. Barnes, R. W. Farndale, and R. Liddington, unpublished results.



## Multiple Discontinuous Ligand-mimetic Antibody Binding Sites Define a Ligand Binding Pocket in Integrin $\alpha_{IIb}\beta_3$ \*

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Integrin  $\alpha_{IIb}\beta_3$ , a platelet fibrinogen receptor, is critically involved in thrombosis and hemostasis. However, how ligands interact with  $\alpha_{IIb}\beta_3$  has been controversial. Ligand-mimetic anti- $\alpha_{IIb}\beta_3$  antibodies (PAC-1, LJ-CP3, and OP-G2) contain the RGD-like RYD sequence in their CDR3 in the heavy chain and have structural and functional similarities to native ligands. We have located binding sites for ligand-mimetic antibodies in  $\alpha_{IIb}$  and  $\beta_3$  using human-to-mouse chimeras, which we expect to maintain functional integrity of  $\alpha_{IIb}\beta_3$ . Here we report that these antibodies recognize several discontinuous binding sites in both the  $\alpha_{IIb}$  and  $\beta_3$  subunits; these binding sites are located in residues 156–162 and 229–230 of  $\alpha_{IIb}$  and residues 179–183 of  $\beta_3$ . In contrast, several nonligand-mimetic antibodies (e.g. 7E3) recognize single epitopes in either subunit. Thus, binding to several discontinuous sites in both subunits is unique to ligand-mimetic antibodies. Interestingly, these binding sites overlap with several (but not all) of the sequences that have been reported to be critical for fibrinogen binding (e.g. N-terminal repeats 2–3 but not repeats 4–7, of  $\alpha_{IIb}$ ). These results suggest that ligand-mimetic antibodies and probably native ligands may make direct contact with these discontinuous binding sites in both subunits, which may constitute a ligand-binding pocket.

Integrin  $\alpha_{IIb}\beta_3$  is a platelet fibrinogen receptor that is critically involved in platelet aggregation (1). Thus  $\alpha_{IIb}\beta_3$ -fibrinogen interaction is a therapeutic target for thrombosis and hemostasis. However, how ligands interact with the integrin  $\alpha_{IIb}$  and  $\beta_3$  subunits has been the subject of much discussion.

The  $\alpha_{IIb}$  subunit has seven repeated sequences of 60–70 residues each in its N-terminal portion. Two different regions of the  $\alpha_{IIb}$  subunit have been implicated in ligand binding. The second metal binding site of  $\alpha_{IIb}$  (residues 294–314 in N-terminal repeat 5 of  $\alpha_{IIb}$ ) has been identified as a ligand binding site by chemically cross-linking the  $\gamma$ -peptide (HHLGGAKQ-AGDV<sup>400–411</sup>) of the fibrinogen  $\gamma$  chain C-terminal domain (2). Both the peptide derived from this  $\alpha_{IIb}$  sequence and its antibodies have been shown to block fibrinogen binding to  $\alpha_{IIb}\beta_3$  (3). Consistently, recombinant bacterial proteins that consist of

repeats 4–7 of  $\alpha_{IIb}$  (residues 171–464) have been shown to bind to ligands in a cation-dependent manner (4). On the other hand, alanine-scanning mutagenesis (5)<sup>1</sup> suggests that the predicted loops in repeats 2 and 3 are critical for ligand binding. Also, function-blocking anti- $\alpha_{IIb}\beta_3$  monoclonal antibodies (mAbs)<sup>2</sup> are mapped in repeats 2 and 3 (5).<sup>1</sup> It has not been established which regions of  $\alpha_{IIb}$  actually interact with ligands.

The presence of an I-domain-like structure within the  $\beta$  subunit has been suggested based on the similarity in hydrophathy profiles between the I-domain of the  $\alpha_M$  subunit and part of the  $\beta$  subunit (6). The N-terminal region of the  $\beta_3$  subunit has components that are critical for ligand binding and its regulation (reviewed in Ref. 7). The RGD-containing peptide chemically cross-links to the N-terminal region (residues 109–171) of the  $\beta_3$  subunit (8). Several different  $\beta_3$  sequences, MDLSYSMKDDLWSI (residues 118–131) (9), DDLW (residues 126–129 of  $\beta_3$ ) (10), DAPEGGFDAIMQATV (residues 217–231 of  $\beta_3$ ) (11, 12), and VSRNRDAPEG (residues 211–221 of  $\beta_3$ ) (13, 14) have been implicated in ligand interaction. The disulfide-linked CYDMKTTC sequence (residues 177–184 in  $\beta_3$ ) in a large predicted loop is critical for the ligand specificity of  $\alpha_v\beta_3$  (15). There are several residues that are critical for ligand binding in the putative I-domain-like structure of  $\beta$  subunits (16–22). These critical oxygenated residues are located in several separate predicted loop structures within the I-domain-like structure of the  $\beta$  subunit (15). It has not been established how these predicted loops, which are critical for ligand binding and specificity, are organized. Two distinct models of the putative I-domain-like structure of  $\beta$  subunits have been published based on the structure of the  $\beta_M$  I-domain (21, 23). It has also been proposed that there is no I-domain-like structure in the  $\beta_3$  subunit (24).

Three anti-human  $\alpha_{IIb}\beta_3$ -specific mAbs, PAC-1 (25), OP-G2 (26), and LJ-CP3 (27), have the tripeptide RYD sequence that mimics the RGD sequence in the CDR3 region of the heavy chain. These mAbs inhibit both fibrinogen binding to platelets and fibrinogen-dependent aggregation of platelets. Binding of these mAbs is cation-dependent and is completely blocked by RGD-containing peptides. PAC-1 does not bind to nonactivated platelets (25). OP-G2 and LJ-CP3 can bind to nonactivated  $\alpha_{IIb}\beta_3$ , but this binding increases upon activation. The ligand-mimetic properties of these mAbs suggest that they have structural and functional similarities to ligands (e.g. fibrinogen). Structure-function studies of these mAbs indicate that the RYD sequence in the CDR3 in their heavy chain occupies the same space as RGD does in conformationally constrained, bioactive  $\alpha_{IIb}\beta_3$  ligands (28).

In the present study, to clarify the controversies surrounding

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The nucleotide sequence(s) reported in this paper has been submitted to the GenBank™/EBI Data Bank with accession number(s) AF166384 (mouse integrin  $\alpha_{IIb}$ ).

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<sup>1</sup> T. Kamata, K. K. Tieu, A. Irie, T. A. Springer, and Y. Takada, unpublished data.

<sup>2</sup> The abbreviations used are: mAb monoclonal antibody; CHO, Chinese hamster ovary; FITC, fluorescein isothiocyanate; PE, phycoerythrin.



$\alpha_{IIb}\beta_3$ -ligand interaction, we studied how ligand-mimetic mAbs as model ligands recognize  $\alpha_{IIb}$  and  $\beta_3$ . We found that these mAbs uniquely recognize several discontinuous binding sites in both  $\alpha_{IIb}$  and  $\beta_3$ . These binding sites overlap with several (but not all) of the sequences that have previously been reported to be critical for fibrinogen binding (e.g. N-terminal repeats 2–3, but not repeats 4–7, of  $\alpha_{IIb}$ ). These results strongly suggest that native ligands make direct contact with these discontinuous binding sites, which may constitute a ligand binding pocket at the  $\alpha/\beta$  boundary.

#### EXPERIMENTAL PROCEDURES

##### *Monoclonal Antibodies and cDNAs*

The specificities of the mAbs used in this study are shown in Table I. mAbs 15 and D57 (29) are a kind gift from M. H. Ginsberg (The Scripps Research Institute). AP-2 (30) is from T. Kunicki (The Scripps Research Institute). 2G12 (31) is from V. Woods (University of California San Diego, San Diego, CA). PL98DF6 (32) is from J. Ylanne (University of Helsinki, Helsinki, Finland). PAC-1 and AZA9 (52) are from S. J. Shattil (The Scripps Research Institute). OP-G2 (33) is from S. Tomiyama (Osaka University, Osaka, Japan). LJ-CP3, LJ-CP8 and LJ-P9 (27) are from Z. M. Ruggeri (The Scripps Research Institute). PT25-2 (34) is from M. Handa and Y. Ikeda (Keio University, Tokyo, Japan). 16N7C2 (35) is from H. Deckmyn (Center for Molecular and Vascular Biology, Leuven, Belgium). 7E3 (36) is a kind gift of B. S. Coller (Mount Sinai Hospital, New York). LM609 (37) is a kind gift of D. Cheresch (The Scripps Research Institute).

##### *Methods*

**Construction and Transfection of cDNAs for Human  $\alpha_{IIb}$  and  $\beta_3$  Mutants**—Human  $\alpha_{IIb}$  and  $\beta_3$  cDNAs were obtained from J. C. Loftus (The Scripps Research Institute). The mouse  $\alpha_{IIb}$  cDNA clone from the mouse EST data base was obtained from American Type Culture Collection (clone 1498358) and partially sequenced by ABI automatic sequencer at the Scripps protein and nucleic acid core facility (GenBank™ accession number AF166384). Wild-type human  $\alpha_{IIb}$  and  $\beta_3$  cDNAs were subcloned into pBJ-1 vector. Site-directed mutagenesis was carried out as described (38). The presence of the mutation was verified by DNA sequencing. Wild-type and mutant  $\alpha_{IIb}$  cDNA constructs in pBJ-1 vector were transfected by electroporation into CHO (Chinese hamster ovary) cells ( $1 \times 10^7$  cells) homogeneously expressing human  $\beta_3$  ( $\beta_3$ -CHO) or into parent untransfected CHO cells together with wild-type human  $\beta_3$  cDNA in pBJ-1, as described previously (5). We obtained essentially the same results either way. Wild-type and mutant  $\beta_3$  cDNAs were transfected into CHO-K1 cells together with wild-type  $\alpha_{IIb}$  cDNA. Cells were harvested 48 h after transfection and used for antibody and/or fluorescein isothiocyanate (FITC)-labeled fibrinogen and PAC-1 binding assays. Mouse  $\alpha_{IIb}$  cDNA encoding the N-terminal 443 residues was fused to the human  $\alpha_{IIb}$  cDNA using an *NheI* site after the *NheI* site was introduced into the human  $\alpha_{IIb}$  cDNA at the corresponding position.

**Binding of FITC-labeled Fibrinogen and mAb PAC-1 to CHO Cells**—Fibrinogen (Enzyme Research Laboratories, South Bend, IN) was labeled with FITC as described previously (39, 40). mAb PAC-1 was labeled with FITC essentially as described (41). Fibrinogen binding to cells transiently expressing  $\alpha_{IIb}\beta_3$  was determined as described previously (42) with some modifications. Briefly, cells were first incubated with PL98DF6 followed by phycoerythrin (PE)-conjugated anti-mouse IgG (BIOSOURCE, Camarillo, CA). After washing, cells were incubated with FITC-labeled fibrinogen or PAC-1 in the presence of control mouse IgG or PT25-2 in 5 mM Hepes/Tyrode, 2 mM  $Ca^{2+}$ , and 2 mM  $Mg^{2+}$  buffer, pH 7.4. Binding of FITC-labeled fibrinogen or PAC-1 to PE-labeled cells expressing high level  $\alpha_{IIb}\beta_3$  was examined in FACScan.

**Flow Cytometry**—Flow cytometric analysis was performed as described (43). To normalize the data for  $\alpha_{IIb}\beta_3$  expression, % expression of each binding site in mutant  $\alpha_{IIb}$  was first normalized using %  $\alpha_{IIb}$  expression with mAb PL98DF6 for  $\alpha_{IIb}\beta_3$  complex-specific mAbs. For the anti- $\beta_3$  mAbs 7E3 and 16N7C2, % expression of each binding site in mutant  $\alpha_{IIb}$  was first normalized using %  $\beta_3$  expression with mAb 15 (normalized % expression). Data is shown as the normalized % of expression in mutants relative to wild-type. Binding sites for mAbs PL98DF6 and 15 were not found in the  $\alpha_{IIb}$  and  $\beta_3$  regions tested in this study (data not shown).

TABLE I  
mAbs used in this study

mAbs	Specificity	Characteristics
LJ-CP3, OP-G2, PAC-1	$\alpha_{IIb}\beta_3$	Ligand-mimetic, the RYD motif in the heavy chain CDR3
16N7C2	$\beta_3$	Inhibitory, the RGD motif in the heavy chain CDR3
7E3	$\beta_3$	Inhibitory
2G12, A2A9, AP-2, LJ-CP8, LJ-P9	$\alpha_{IIb}\beta_3$	Inhibitory
PT25-2	$\alpha_{IIb}\beta_3$	Activating
D57	$\alpha_{IIb}\beta_3$	Nonfunctional
LM609	$\alpha_v\beta_3$	Inhibitory
PL98DF6	$\alpha_{IIb}$	Nonfunctional
15	$\beta_3$	Nonfunctional

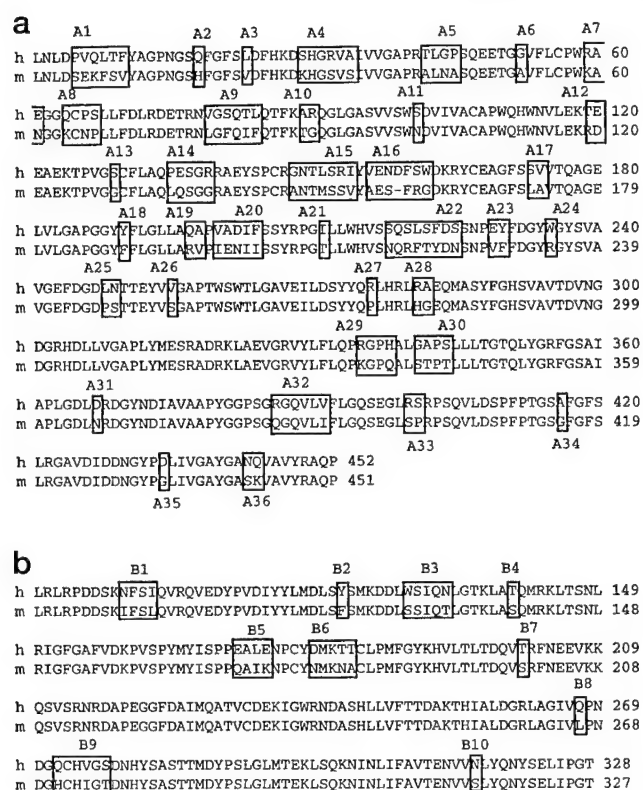
#### RESULTS

**Ligand-mimetic mAbs Recognize Several Discontinuous N-terminal Regions of the  $\alpha_{IIb}$  Subunit**—We used human-to-mouse  $\alpha_{IIb}$  and  $\beta_3$  mutations to localize binding sites for three ligand-mimetic mAbs and several function-blocking or -activating mAbs (Table I). The rationale behind this strategy is that all of the mAbs used in this study recognize human  $\alpha_{IIb}\beta_3$  but not mouse  $\alpha_{IIb}\beta_3$ . We also expect this strategy to enable for us to maintain the ligand binding function of the mutants while eliminating the potential problems associated with mutation of individual residues to Ala, which could indirectly induce conformational changes.

Since the mouse  $\alpha_{IIb}$  sequence has not been published, we first sequenced the N-terminal region of putative mouse  $\alpha_{IIb}$  cDNA clones from the mouse EST cDNA data base (Fig. 1a). The N-terminal seven-repeat region of human  $\alpha_{IIb}$  is 82.5% identical to that of mouse  $\alpha_{IIb}$  (they have 452 and 451 amino acid residues, respectively). To determine whether binding sites for ligand-mimetic and nonligand-mimetic mAbs are located in the seven-repeat region of  $\alpha_{IIb}$ , we first replaced N-terminal 443 amino acid residues of human  $\alpha_{IIb}$  with the corresponding sequence of mouse  $\alpha_{IIb}$ . The human/mouse  $\alpha_{IIb}$  chimera was transiently transfected into  $\beta_3$ -CHO cells that homogeneously express wild-type human  $\beta_3$ . Reactivity of the transfected cells to a panel of mAbs is shown in Table II. The results indicate that the anti- $\alpha_{IIb}\beta_3$  mAbs tested recognize  $\alpha_{IIb}\beta_3$  but not  $\alpha_v\beta_3$ . All of the  $\alpha_{IIb}\beta_3$  mAbs tested, except for AP-2 and D57, require the N-terminal 443-amino acid residues of human  $\alpha_{IIb}$  for  $\alpha_{IIb}\beta_3$  recognition. AP-2 and D57 require the  $\alpha_{IIb}$  subunit but do not require the human N-terminal 443 residues. The anti- $\alpha_{IIb}$  mAb PL98DF6 does not require the human N-terminal 443 residues.

We introduced human-to-mouse mutations, alone or in groups, into the N-terminal seven-repeat region of human  $\alpha_{IIb}$  to identify  $\alpha_{IIb}$  sequences that are critical for antibody binding (Fig. 1a). The human-to-mouse  $\alpha_{IIb}$  mutants were individually transfected into  $\beta_3$ -CHO cells. The capacity of transiently expressed  $\alpha_{IIb}\beta_3$  mutants to bind to a panel of mAbs (listed in Table I) was tested using flow cytometry. Fig. 2 shows flow cytometric profiles of wild-type  $\alpha_{IIb}\beta_3$  and the A16 mutant (V156A/N158S/D159 deletion/S161R/W162G) as an example. 30–50% of cells transfected with wild-type  $\alpha_{IIb}\beta_3$  are positive with LJ-CP3, OP-G2, and PT25-2. 30–50% of cells expressing the A16 mutant are positive with PT25-2, but almost none of them are positive with LJ-CP3 and OP-G2. This indicates that the mutant is expressed on the cell surface but does not react with LJ-CP3 and OP-G2.

The results for 36 mutants are summarized in Table III (data is shown only for selected mutants). Because expression levels vary, we normalized the percentage of positive cells for each mutant. We used PL98DF6 (an anti- $\alpha_{IIb}$  mAb) to normalize the  $\alpha_{IIb}\beta_3$  expression and mAb 15 (an anti- $\beta_3$  mAb) to normalize



**FIG. 1. Alignment of human and mouse  $\alpha_{IIb}$  (a) and  $\beta_3$  (b) subunits.** a, in the N-terminal seven-repeat regions of human (h) and mouse (m)  $\alpha_{IIb}$ , the amino acid sequences are different at 79 positions. Human-to-mouse mutations alone or in groups (36 total) were introduced and designated A1-36. Positions of mutations in the human-to-mouse  $\alpha_{IIb}$  mutants are A1, P5S/V6E/Q7K/L8F/T9S/F10V; A2, Q18H; A3, L23V; A4, S29K/R32S/A34S; A5, T42A/G44N/P45A; A6, G52A; A7, R59K/E61N; A8, Q64K/P66N/S67P; A9, V79L/S81F/T83L/L84F; A10, A89T/R90G; A11, S101N; A12, T119R/E120D; A13, S129G; A14, P135L/E136Q/R139G; A15, G148A/L151M/R153S/I154V; A16, V156A/N158S/D159 deletion/S161R/W162G; A17, S173L/V174A; A18, Y190F; A19, Q197R/A198V; A20, V200I/A201E/D202N/F204I/S206T; A21, I211T; A22, S218N/S220R/L221F/S222T/F223Y/S225N; A23, E229V/Y230F; A24, W235R; A25, L248P/N249S; A26, V255S; A27, R276P; A28, R281H/A282G; A29, R335K/H338Q; A30, G341S/A342T/S344T; A31, D367N; A32, R386E/V391I; A33, R400S/S401P; A34, A416G; A35, D434G; and A36, N443S/Q444K. b, the amino acid sequences of human and mouse  $\beta_3$  are different at 17 positions. Human-to-mouse mutations, alone or in groups (10 total), were introduced and designate B1-10. Positions of mutations in the human-to-mouse  $\beta_3$  mutants are B1, N99I/I102L; B2, Y122F; B3, W129S/N133T; B4, T140S; B5, E171Q/L173I/E174K; B6, D179N/T182N/T183A; B7, T201S; B8, Q267L; B9, Q272H/V275I/S277T; and B10, N316S.

the  $\beta_3$  expression. Data are presented as the ratio of the mutant cells that are positive to mAbs to the wild-type cells that are positive to mAbs. We found that LJ-CP3 binding is completely blocked by the A16 mutation and almost completely blocked by the A23 mutation (E229V/Y230F). OP-G2 binding is almost completely blocked by the A16 mutation. Binding of non-ligand-mimetic function-blocking mAbs LJ-P9 and LJ-CP8 is completely blocked by the A9 mutation (V79L/S81F/T83L/L84P) and by the A16 mutation, respectively. Binding of activating mAb PT25-2 was completely blocked by the A29 (R335K/H338Q) mutation. 32 other mutations (listed in Fig. 1a and its legend) did not significantly affect the binding of the mAbs tested. The A16 mutation blocks binding of LJ-CP3, OP-G2, and LJ-CP8, but the nearby A15 and A17 mutations do not affect binding of these mAbs. Also, the A9, A16, A23, and A29 mutations specifically block binding of one or three mAbs, but not others, indicating that the human-to-mouse mutations do not induce global conformational changes, and their effects remain local.

**Ligand-mimetic mAbs Recognize Discontinuous N-terminal Regions of the  $\beta_3$  Subunit**—There are 17-amino acid-residue differences between human and mouse  $\beta_3$  in the putative I-domain-like region spanning residues 90–328 (Fig. 1b). We introduced human-to-mouse mutations into the putative I-domain-like region of human  $\beta_3$  alone or in-groups. The human-to-mouse  $\beta_3$  mutants (total 10) were transiently expressed together with wild-type  $\alpha_{IIb}$  cDNA on CHO cells. Since CHO cells express endogenous  $\alpha_v$ , but do not express  $\beta_3$ , the human  $\beta_3$  subunit is expressed as human  $\alpha_{IIb}\beta_3$  and hamster  $\alpha_v$ /human  $\beta_3$ . The ability of  $\alpha_{IIb}\beta_3$  or  $\alpha_v\beta_3$  to bind to a panel of mAbs (Table I) was tested in flow cytometry. We found that several human-to-mouse mutations affect binding of function-blocking mAbs (Table IV). Binding of mAb 16N7C2 (anti- $\beta_3$ , RGD+) is completely blocked by the B3 (W129S/N133T) mutation. Binding of 7E3 and A2A9 is completely blocked by the B6 (D179N/T182N/T183A) mutation and partially blocked by the B3 mutation. Binding of AP-2 and LM609 is completely blocked by the B5 (E171Q/L173I/E174K) mutation. In contrast, these mutations only partially blocked the binding of ligand-mimetic mAbs. Binding of OP-G2 and LJ-CP3 is partially blocked by the B6 mutation.

To determine whether the B6 mutation really affects OP-G2 or LJ-CP3 binding, we studied the effects of combined mutations on OP-G2 and LJ-CP3 binding. The combined B3/B6 mutation completely blocked LJ-CP3 binding and almost completely blocked OP-G2 binding. However, the combined B3/B5 or B6/B9 mutation had only a modest effect on OP-G2 and LJ-CP3 binding. These results suggest that the B3 and B6 binding sites are involved in OP-G2 and LJ-CP3 binding, but the nearby B5 and B9 sites (controls) are probably much less involved (Table V). However, binding of several nonligand-mimetic mAbs (e.g. 16N7C2) was not affected by the combined mutations tested. We did not find any  $\beta_3$  mutations that affect the binding of mAbs 2G12, LJ-CP8, and LJ-P9.

**Effect of Human-to-mouse Mutation on Activation-dependent PAC-1 and Fibrinogen Binding**—We studied the effect of the several mutations that affect binding of ligand-mimetic mAbs on the activation-dependent binding of PAC-1 (Fig. 3). Binding of FITC-labeled PAC-1 was determined as the difference in FITC fluorescence signal (FL-1) in the presence and absence of the activating anti- $\alpha_{IIb}\beta_3$  mAb PT25-2 in the PE-positive ( $\alpha_{IIb}$  positive, FL-2) cell population (Fig. 3a). PT25-2 activates  $\alpha_{IIb}\beta_3$  but does not activate  $\alpha_v\beta_3$  (PT25-2 is specific to  $\alpha_{IIb}\beta_3$ ). PAC-1 binding was completely blocked by the A16 mutation and was reduced by the A23 mutation. PAC-1 binding was partly blocked by the B6 mutation but not by the B3, B5, or control B7 mutation. The combined B3/B6 mutations did not further reduce PAC-1 binding. These results suggest that activation-dependent PAC-1 is similar to LJ-CP3 and OP-G2 in that site A16 is critical for binding, and several other sites (sites A23 and B6) are involved in binding.

Binding of soluble fibrinogen to these mutants was studied to determine whether these mutants still bind to ligands. Binding of FITC-labeled fibrinogen was determined as the difference in FITC fluorescence signal in the presence and absence of the activating mAb PT25-2 in the PE-positive ( $\alpha_{IIb}$  positive) cell population (Fig. 3b). Fibrinogen bound to the A16 and B6 mutants at a level comparable to or higher than that of wild-type and the control B7 mutant. Binding of soluble fibrinogen to the A23 mutant was lower than that of wild-type or the control mutants, but still detectable. These results suggest that the A16, A23, B3, and B6 mutants still maintain the integrity and ligand binding function of  $\alpha_{IIb}\beta_3$ . Although the fibrinogen binding function appears to vary from mutant to mutant, this may reflect the reported potential species dif-

TABLE II  
Specificity of anti- $\alpha_{IIb}\beta_3$  mAbs to human  $\alpha_{IIb}$

Human  $\alpha_{IIb}$ , with mouse residues 1–443 was transiently expressed in  $\beta_3$ -CHO cells (which homogeneously express human  $\beta_3$ ). Cells were stained with primary mAbs and then FITC-labeled goat anti-mouse IgG and analyzed by flow cytometry. Data are expressed as % positive cells. Clonal  $\beta_3$ -CHO cells (which express hamster  $\alpha$ /human  $\beta_3$  hybrid) and  $\alpha_{IIb}\beta_3$ -CHO cells (which express both hamster  $\alpha$ /human  $\beta_3$  hybrid and human  $\alpha_{IIb}\beta_3$ ) were used as controls. Parent CHO cells do not express  $\alpha_{IIb}\beta_3$ .

	Parent CHO	$\beta_3$ -CHO	$\alpha_{IIb}\beta_3$ -CHO	Mouse/human $\alpha_{IIb}/\beta_3$
Mouse IgG	0.96	2.81	1.5	1.35
PL98DF6	1.28	2	52.66 <sup>a</sup>	49.36 <sup>a</sup>
mAb 15	1.68	88.75 <sup>a</sup>	91.82 <sup>a</sup>	91.27 <sup>a</sup>
PT25-2	1.71	1.63	59.76 <sup>a</sup>	2.26
D57	1.78	2.1	72.73 <sup>a</sup>	69.87 <sup>a</sup>
2G12	1.64	1.6	65.45 <sup>a</sup>	3.35
A2A9	1.85	2.02	61.1 <sup>a</sup>	1.64
AP-2	2.33	1.97	63.61 <sup>a</sup>	59.44 <sup>a</sup>
LJ-CP8	1.67	1.83	56.34 <sup>a</sup>	2.08
LJ-P9	1.55	1.92	71.88 <sup>a</sup>	1.53
OP-G2	2.24	2.15	55.93 <sup>a</sup>	1.01
LJ-CP3	1.83	2.39	38.81 <sup>a</sup>	1.21

<sup>a</sup> Positive reactivity.

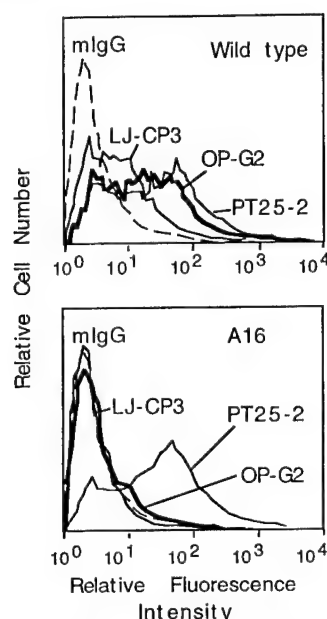


FIG. 2. Binding of mAbs to wild-type and mutant  $\alpha_{IIb}\beta_3$  that are transiently expressed on CHO cells. Wild-type or mutant  $\alpha_{IIb}$  cDNA in pBJ-1 vector was transfected into CHO cells together with wild-type human  $\beta_3$  cDNA in pBJ-1 vector. After 48 h, cells were harvested and stained first with mAbs LJ-CP3, OP-G2, PT25-2, or control mouse IgG (mIgG) and then with FITC-labeled goat anti-mouse IgG. Wt  $\alpha_{IIb}\beta_3$  is recognized by all of the anti- $\alpha_{IIb}\beta_3$  mAbs tested. The A16 mutant is recognized by PT25-2 but not by LJ-CP3 or OP-G2.

ference in  $\alpha_{IIb}\beta_3$  function (44).

**Role of the Predicted Loop (Residues 177–184) of  $\beta_3$  in Binding to Ligand-mimetic mAbs and Fibrinogen**—To determine whether the predicted loop of  $\beta_3$  (Residues 177–184) that contains site B6 is involved in the binding of ligands and ligand-mimetic mAbs to  $\alpha_{IIb}\beta_3$ , we swapped this predicted loop of  $\beta_3$  with the corresponding sequence of  $\beta_1$ . The resulting  $\beta_{3-1-3}$  mutant cDNA was transfected into CHO cells together with wild-type  $\alpha_{IIb}$  cDNA and a neomycin-resistant gene. Cells stably expressing  $\alpha_{IIb}\beta_{3-1-3}$  were cloned by sorting. Binding of mAbs and fibrinogen was studied by flow cytometry (Table VI). Expression of  $\alpha_{IIb}$  was normalized using the anti- $\alpha_{IIb}$  mAb PL98DF6. The results suggest that the  $\beta_{3-1-3}$  mutation significantly blocks binding of  $\alpha_{IIb}\beta_3$  to OP-G2, LJ-CP3, and fibrinogen. The mutation did not affect binding to control mAb 15 (anti- $\beta_3$ ). This suggests that the predicted loop may be critically involved in the binding of  $\alpha_{IIb}\beta_3$  to ligand-mimetic mAbs and fibrinogen.

## DISCUSSION

**What Do the Discontinuous Binding Sites in  $\alpha_{IIb}$  for Ligand-mimetic mAbs Tell Us about Structure and Function of  $\alpha_{IIb}$ ?**—The present study provides evidence that two discontinuous sites in  $\alpha_{IIb}$  (A16 and A23) are critical for binding to ligand-mimetic mAbs. Several regions/residues that are critical for ligand binding in  $\alpha_{IIb}$  have been identified by site-directed mutagenesis or by genetic analysis of natural function-defective  $\alpha_{IIb}\beta_3$  mutants (see the Introduction), but whether these regions/residues directly interact with ligands has been unclear. Interestingly, the discontinuous ligand-mimetic mAb binding sites overlap with or are close to several conserved critical residues for ligand binding that have been identified by alanine-scanning mutagenesis (Fig. 4a). It should be noted that these conserved critical residues are not changed in human-to-mouse mutations. Site A16 is localized in the predicted loop at the boundary between repeats 2 and 3 of  $\alpha_{IIb}$ . We have found that mutating conserved residues Arg-147, Tyr-155, Phe-160, Asp-163, or Arg-165 to Ala blocks binding of fibrinogen and/or ligand-mimetic mAbs (Fig. 4a).<sup>1</sup> It has been reported that a patient with Glanzmann's thrombasthenia, who has function-defective  $\alpha_{IIb}$ , has a two-amino acid insertion (Arg-Thr) between residues 160 and 161 in this region of the  $\alpha_{IIb}$  subunit (45). Mutating Asp-163 in this predicted loop of  $\alpha_{IIb}$  to Ala has been shown to block binding of fibrinogen and ligand-mimetic mAbs (45). Site A23 is recognized by the ligand-mimetic mAb LJ-CP3, and is located in the predicted loop at the boundary between repeats 3 and 4 of the  $\alpha_{IIb}$  subunit. The nearby D224V mutation of  $\alpha_{IIb}$  has recently been shown to block PAC-1 and OP-G2 binding to  $\alpha_{IIb}\beta_3$  (46). However, the function of this region has not been identified. We have found that mutating conserved Ser-222, Asp-224, Phe-231, or Asp-232 to Ala blocks binding to fibrinogen and ligand-mimetic mAbs (Fig. 4a).<sup>1</sup> The fact that sites A16 and A23 overlap with the  $\alpha_{IIb}$  regions that are critical for ligand binding indicates that these residues/regions make direct contact with native ligands. These results are consistent with the proposed  $\beta$ -propeller model of the  $\alpha$  subunit (47) in that sites A16 and A23, which are believed to make direct contact with ligands, are spatially close to each other, even though they are separate in the primary structure. In this model, site A9 (an epitope for mAb LJ-P9) is spatially close to sites A16 and A23 (Fig. 5). This is consistent with the function-blocking activity of mAb LJ-P9.

It is possible that site A16 is critically involved in RYD recognition and binding, since site A16 is recognized by all of the RYD-containing ligand-mimetic mAbs, and the A16 mutation completely blocks binding of these mAbs (the effect of the A23 mutation and the human-to-mouse mutations in  $\beta_3$  on the

TABLE III  
Effects of human-to-mouse mutations in  $\alpha_{IIb}$  on  $\alpha_{IIb}\beta_3$  binding to mAbs

The human-to-mouse  $\alpha_{IIb}$  mutants were transiently expressed in CHO cells together with wild-type human  $\beta_3$ . After 48 h, cells were tested for their ability to bind to a panel of anti- $\alpha_{IIb}\beta_3$  mAbs in flow cytometry. Data are expressed as the ratio % positive cells with the mutant  $\alpha_{IIb}\beta_3$  to % positive cells with wild type. The data were first normalized for expression, then binding of mAbs relative to wild type was calculated. The % expression of PL98DF6 (a nonfunctional anti- $\alpha_{IIb}$  mAb) was used to normalize the expression of  $\alpha_{IIb}\beta_3$  (for LJ-CP3, OP-G2, LJ-CP8, 2G12, PT25-2, LJ-P9, AP2, and A2A9). The % expression of mAb 15 (a nonfunctional anti- $\beta_3$  mAb) was used to normalize the expression of  $\beta_3$  (for D57, 7E3, and 16N7C2). Of the human-to-mouse  $\alpha_{IIb}$  mutants tested in this study, only A9, A16, A23, and A29 had a noticeable effect on binding of mAbs tested.

	Wild type	A2	A5	A9	A15	A16	A17	A23	A24	A29
LJ-CP3	1	1.33	0.91	1.02	1.38	0	1.11	0.13	1.02	1.24
OP-G2	1	0.88	0.93	0.84	0.86	0.05	1.02	0.75	0.92	0.89
16N7C2	1	0.98	0.99	0.97	0.99	1.00	0.99	0.98	0.96	0.98
2G12	1	0.72	0.86	0.68	0.72	0.88	1.21	0.94	0.81	0.79
7E3	1	0.98	0.96	0.99	0.99	0.96	0.96	0.96	0.95	0.96
A2A9	1	1.10	1.11	0.96	0.95	0.80	0.80	0.85	0.87	1.10
AP-2	1	1.11	1.05	0.97	0.99	0.92	0.99	1.00	1.04	1.15
LJ-CP8	1	0.83	0.93	0.78	0.81	0	1.11	0.88	0.89	0.88
LJ-P9	1	1.01	0.84	0	0.96	1.17	1.00	1.00	0.80	0.74
PT25-2	1	0.76	0.87	0.74	0.76	1.00	1.06	0.96	0.86	0
D57	1	1.12	0.96	1.04	1.15	1.05	0.85	0.96	1.10	1.15

TABLE IV  
Effects of  $\beta_3$  human-to-mouse mutations on  $\alpha_{IIb}\beta_3$  binding to mAbs

The human-to-mouse  $\beta_3$  mutants were transiently expressed in CHO cells together with wild-type human  $\alpha_{IIb}$ . Data are expressed as the ratio % positive cells with the mutant  $\alpha_{IIb}\beta_3$  to % positive cells with wild type. Analysis of the reactivity of a panel of mAbs to mutant  $\alpha_{IIb}\beta_3$  in flow cytometry and normalization of the results were performed as described in the legend to Table III.

	Wild type	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
LJ-CP3	1	0.92	0.88	0.90	1.00	0.96	0.25	1.08	0.65	0.89	0.91
OP-G2	1	0.93	0.95	0.79	1.11	0.91	0.57	1.03	0.82	1.18	1.18
16N7C2	1	1.08	1.00	0	1.03	1.00	0.82	0.98	1.06	1.07	1.01
2G12	1	1.04	0.91	1.34	1.10	0.98	1.04	0.93	0.89	1.10	0.92
7E3	1	1.01	1.01	0.58	0.96	1.05	0	1.04	0.91	0.94	1.07
A2A9	1	0.89	1.06	0.69	0.92	0.95	0	0.98	0.87	0.95	1.07
AP-2	1	0.95	1.02	0.92	0.96	0	0.93	1.01	0.95	0.96	1.05
LJ-CP8	1	1.00	0.94	1.16	1.07	0.99	1.08	0.99	0.99	1.13	0.87
LJP9	1	1.06	0.88	1.33	1.13	0.98	1.02	0.96	0.96	1.09	0.91
LM609	1	1.00	0.97	1.03	1.01	0	0.89	0.89	1.13	1.03	1.00
PT25-2	1	1.00	0.90	1.19	1.08	0.98	1.01	0.93	0.94	1.04	0.87
D57	1	0.98	1.03	0.91	0.95	0.20	0.97	1.05	0.95	0.99	1.09

TABLE V  
Effects of combined mutations on binding of mAbs to  $\alpha_{IIb}\beta_3$

Human-to-mouse  $\beta_3$  mutants with combined  $\beta_3$  mutations were transiently expressed in CHO cells together with wild-type human  $\alpha_{IIb}$ . Analysis of the reactivity of a panel of mAbs to mutant  $\alpha_{IIb}\beta_3$  in flow cytometry and normalization of the results were performed as described in the legend to Table III.

	Wild-type	B3/B5	B3/B6	B6/B9
LJ-CP3	1	0.43	0	0.49
OPG2	1	0.51	0.05	0.53
16N7C2	1	0	0	0.81
2G12	1	1.30	1.34	1.09
7E3	1	0.66	0	0
A2A9	1	0.72	0	0
AP2	1	0	0.78	0.91
LJ-CP8	1	1.36	1.34	1.36
D57	1	0.13	0.96	0.94

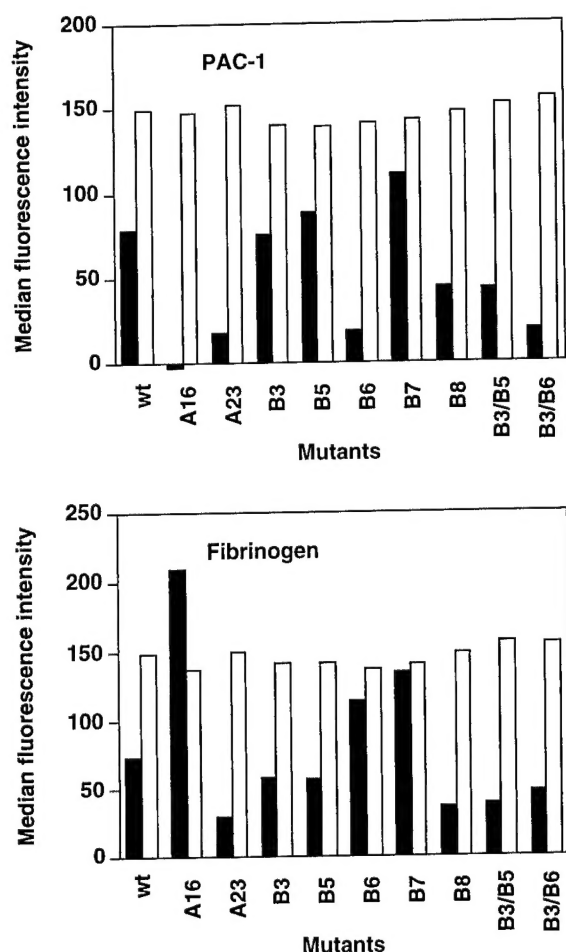
binding of ligand-mimetic antibodies is relatively weak and variable compared with that of the A16 mutation and may depend on antibody species.) It is interesting to note that the A16 mutant shows higher fibrinogen binding than wild-type (Fig. 3), although the A16 mutant does not bind to ligand-mimetic antibodies. It is well known that RGD peptide does not effectively block fibrinogen binding to rat and rabbit (44) and mouse  $\alpha_{IIb}\beta_3$ . It is possible that  $\alpha_{IIb}\beta_3$  from these species may have higher affinity to fibrinogen than human  $\alpha_{IIb}\beta_3$  due to species difference in site A16. Further biochemical studies of site A16 will be required to address this hypothesis.

The present results indicate that ligand-mimetic mAbs do not recognize the region close to the previously reported putative ligand binding ( $\gamma$ -chain peptide cross-linking) site in repeat

5 of  $\alpha_{IIb}$  (2). This suggests that this region is not a major ligand binding site. This idea is consistent with the proposed  $\beta$ -propeller model, since the fibrinogen  $\gamma$ -peptide cross-linking site in repeat 5 of  $\alpha_{IIb}$  is located in the lower face of the domain, a predicted nonligand binding site. The regions critical for ligand binding in repeats 2 and 3 (containing sites A16 and A23) are located in the upper face of the model, a predicted ligand binding site (47). It is intriguing that the activating anti- $\alpha_{IIb}\beta_3$  mAb PT25-2 recognizes site A29 in  $\alpha_{IIb}$ , which is close to the  $\gamma$ -chain peptide cross-linking site. It is possible that the  $\gamma$ -chain peptide cross-linking site might be an allosteric binding site, which is consistent with the location of this site in the predicted nonligand binding site of the  $\beta$ -propeller model.

*What Do the Discontinuous Binding Sites in  $\beta_3$  for Ligand-mimetic mAbs Tell Us about Structure and Function of  $\beta_3$ ?*—Although no single human-to-mouse mutation in the  $\beta_3$  subunit strongly blocks binding of ligand-mimetic mAbs, we provided evidence that the combined B3 and B6 mutation strongly blocks binding of LJ-CP3 and OP-G2 to  $\alpha_{IIb}\beta_3$ . The fact that more than two mutations are required to block binding of mAbs is not surprising if we assume that these mAbs interact with multiple sites in both subunits for binding. The effect of the combined B3 and B6 mutation is significant, since the nearby control B5 or B9 mutation does not increase the effect of the B3 or B6 mutation. These results indicate that sites B3 and B6 are involved in the binding of these ligand-mimetic mAbs, although the B3 mutation alone has no effect. Site B6 is located in the predicted loop (residues 177–184 of  $\beta_3$ ), which has been reported to be critical for ligand binding and specificity (15). Swapping this disulfide-linked predicted loop of  $\beta_1$  with the corresponding  $\beta_3$  sequence changes the ligand specificity of





**FIG. 3. Effect of several human-to-mouse mutations in  $\alpha_{IIb}$  and  $\beta_3$  on activation-dependent PAC-1 and fibrinogen binding.** *a*, PAC-1 binding to wild-type and mutant  $\alpha_{IIb}\beta_3$ . Cells were first incubated with PL98DF6 (anti-human  $\alpha_{IIb}$ ) followed by PE-conjugated anti-mouse IgG. After washing, cells were incubated with FITC-labeled PAC-1 in the presence of control mouse IgG or PT25-2 (activating anti- $\alpha_{IIb}\beta_3$  mAb) in 5 mM Hepes/Tyrosine, 2 mM  $Ca^{2+}$ , and 2 mM  $Mg^{2+}$  buffer, pH 7.4. Binding of FITC-labeled PAC-1 to the PE-labeled  $\alpha_{IIb}$ -positive cell population expressing high level  $\alpha_{IIb}\beta_3$  (fluorescence intensity  $>10^2$ ) was examined in FACSscan. Data are expressed as a difference in median FITC fluorescent intensity in the presence and absence of PT25-2 (solid column). Median PE fluorescence intensity in the cell population used for measurement of PAC-1 binding is shown (open column). The data suggest that PAC-1 binding is completely blocked by the A16 mutation and partly blocked by the A23 and B6 mutations. *b*, fibrinogen binding to wild-type and mutant  $\alpha_{IIb}\beta_3$ . Fibrinogen binding to the cell population expressing high level  $\alpha_{IIb}\beta_3$  was determined as described in *a*, except that FITC-fibrinogen was used instead of FITC-PAC-1. Data are expressed as a difference in median FITC fluorescent intensity in the presence and absence of PT25-2 (solid column). Median PE fluorescence intensity in the PE-labeled  $\alpha_{IIb}$ -positive cell population used for measurement of fibrinogen binding is shown (open column). The data suggest that the mutants tested maintain fibrinogen binding, although the A23 mutant shows relatively low fibrinogen binding, and the A16 mutant shows relatively high fibrinogen binding. Parent CHO cells do not show  $\alpha_{IIb}\beta_3$ -specific fibrinogen binding, since parent CHO cells are PE-negative (FL-2  $<10^2$ ).

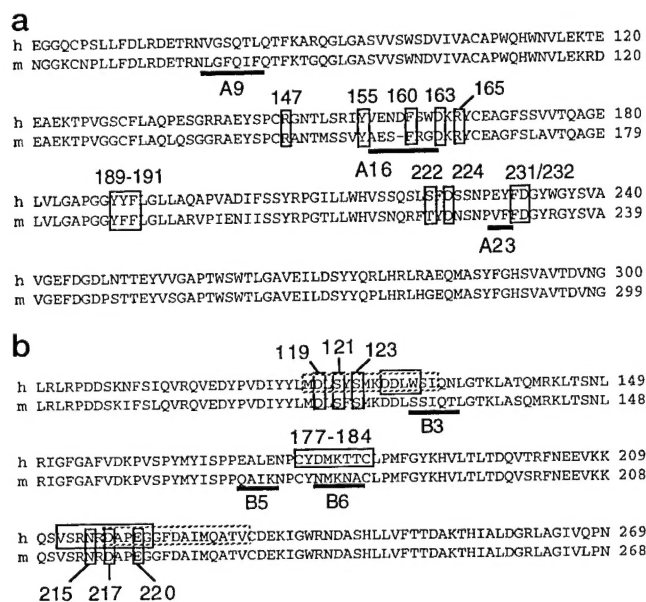
$\alpha_v\beta_3$  (15). Also, fibrinogen C-terminal domains require this predicted loop sequence of  $\beta_3$  for binding to  $\alpha_v\beta_3$  (48). In the present study, we have shown that the  $\beta_{3-1-3}$  mutant blocks binding of  $\alpha_{IIb}\beta_3$  to OP-G2, LJ-CP3, and fibrinogen (Table VI). These results are consistent with the observation that site B6 is involved in the binding of ligand-mimetic mAbs. We found that two function-blocking mAbs, 7E3 and A2A9, also recognize site B6, consistent with their function-blocking activity.

The B3 mutation completely blocks the binding of  $\alpha_{IIb}\beta_3$  to

**TABLE VI**  
Effects of the  $\beta_{3-1-3}$  mutation on  $\alpha_{IIb}\beta_3$  binding to ligand-mimetic mAbs and fibrinogen

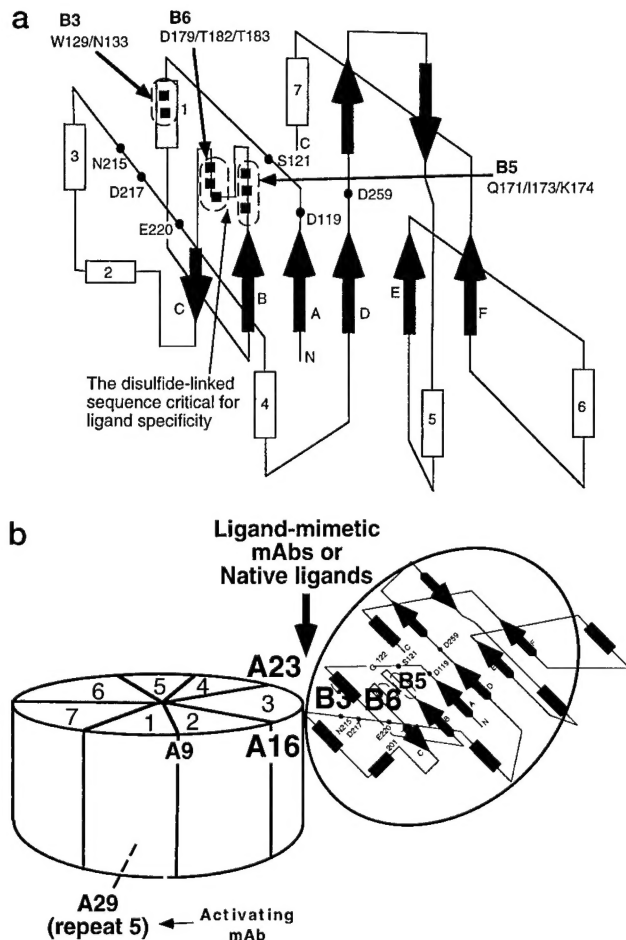
Cloned cells stably expressing wild type or mutant  $\alpha_{IIb}\beta_{3-1-3}$  were used. Reactivity to mAbs and binding of FITC-labeled soluble fibrinogen were assayed by flow cytometry. Data are expressed as the ratio of mean fluorescent intensity. The data suggest that the  $\beta_{3-1-3}$  mutation blocks binding of ligand-mimetic mAbs and fibrinogen to  $\alpha_{IIb}\beta_3$ .

	Wild type $\alpha_{IIb}\beta_3$	$\alpha_{IIb}/\beta_{3-1-3}$	Mutant MFI/wild type MFI ratio
PL98DF6	209 (100)	102 (100)	1
mAb 15	548 (262)	220 (214)	0.82
OP-G2	358 (171)	24.0 (23.3)	0.14
LJ-CP3	134 (64)	3.42 (3.32)	0.052
Fibrinogen	18.7 (8.9)	0.8 (0.78)	0.087



**FIG. 4. Binding sites for function-blocking and/or ligand-mimetic mAbs are close to or overlap with several sequences/residues that are critical for ligand binding and specificity.** *a*, sites A9, A16, and A23 for function-blocking and/or ligand-mimetic mAbs are located at the boundary (the 4-1 loop) between repeats 1 and 2, repeats 2 and 3, and repeats 3 and 4, respectively. Sites A16 and A23 are close to or overlap with conserved residues that are critical for ligand binding (boxed, see Introduction for references). *b*, sites B3 and B6 are close to or overlap with the sequences that are critical for ligand binding or specificity (boxed, see Introduction for references). These results suggest that the conserved critical sequences/residues for ligand binding and specificity that are close to sites A16, A23, B3, and B6 actually make direct contact with ligands.

the RGD-containing anti- $\beta_3$  mAb 16N7C2. It is highly likely that the RGD motif of 16N7C2 is involved in its binding to  $\beta_3$ , since this interaction is blocked by echistatin, an RGD-containing disintegrin (35). Intriguingly, site B3 overlaps with the DDLW sequence (residues 126–129), a putative RGD binding site (Fig. 4). The CWDDGWLC peptide is a functional mimic of the ligand binding sites of RGD-directed integrins (10), and the structurally similar DDLW sequence in the integrin  $\beta$  subunit has been proposed to be a putative RGD binding site. Also, this binding site is part of the MDLSYSMKDDLWSI sequence (residues 118–131), to which the RGD-containing peptide has been reported to make a ternary complex with cations (9). This is consistent with the reports that RGD-containing peptides block binding of these ligand-mimetic mAbs to  $\alpha_{IIb}\beta_3$  (25–27). Nearby Asp-119, Ser-121, and Ser-123 are critical for the binding of ligands and ligand-mimetic mAbs (19, 21, 49). Taken together, the present results are consistent with the idea that the DDLW sequence, which overlaps with site B3, makes direct contact



**FIG. 5. Positions of antibody binding sites for function-blocking or ligand-mimetic mAbs in the putative  $\beta_3$  I-domain (a) and the proposed  $\beta$ -propeller domain (b).** a, the model of the  $\beta_3$  I-domain was taken from Takagi *et al.* (15) and Tuckwell *et al.* (23) and modified. Arrows indicate  $\beta$ -sheets, and columns indicate  $\alpha$ -helices. Closed circles show residues that are critical for ligand binding in  $\beta_1$  or  $\beta_3$  (16). In this model, the diverse disulfide-linked sequence that is critical for ligand specificity (residues 177–184 in  $\beta_3$ ) (15) is located in the predicted loop, surrounded by conserved oxygenated residues in the upper face of the I-domain-like structure of the  $\beta_3$  subunit that are critical for ligand binding (e.g. Asp-119). The upper face of this domain is predicted to be a ligand binding site, based on its homology to the I-domains of  $\alpha_M$  and  $\alpha_L$  (23). Site B3 is located in helix 1 and overlaps the putative RGD binding site (10). Site B6 is located in the predicted disulfide-linked sequence that is critical for ligand specificity (15). It should be noted that all of the binding sites for ligand-mimetic or function-blocking mAbs are located on the same side of the model (the putative ligand site) and are predicted to be close to each other. b, the approximate positions of the  $\alpha_{IIb}$  binding sites are shown. Sites A9, A16, and A23 are located at the boundary between repeats 1 and 2, repeats 2 and 3, and repeats 3 and 4, respectively. Site A29, which is recognized by the activating mAb PT25-2, is located in the lower face (nonligand binding site) of the domain. Also, the potential relative positions of the  $\alpha_{IIb}$  proposed  $\beta$ -propeller domain and the putative  $\beta_3$  I-domain-like structure are shown. In this model, sites A16 and A23 face sites B3 and B6 in the  $\beta_3$  subunit, generating a ligand binding pocket at the  $\alpha/\beta$  boundary.

with ligands through the RGD motif and is part of the ligand binding site.

It has been reported that  $\alpha_{IIb}\beta_3$  may have two distinct ligand binding sites based on kinetic analysis of ligand binding (Refs. 50 and 51 and references therein), but positions of the proposed binding sites are unknown. The RGD-containing mAb 16N7C2 recognizes site B3, which overlaps with the putative RGD binding site in  $\beta_3$ , but this mAb does not require  $\alpha_{IIb}$  subunit for binding. The three ligand-mimetic mAbs recognize site A16, which overlaps with critical residues for ligand binding in  $\alpha_{IIb}$ .

Interestingly, human-to-mouse mutations in  $\beta_3$  (including B3) have relatively minor effects on binding to ligand-mimetic mAbs compared with the A16 mutation (see above). These results suggest that mAb 16N7C2 and the ligand-mimetic mAbs recognize two separate sites in  $\alpha_{IIb}\beta_3$  (B3 and A16, respectively) in an RGD- or RYD-dependent manner. Thus sites A16 and B3 may represent two distinct RGD or RYD recognition and binding sites in  $\alpha_{IIb}\beta_3$ .

We found that several function-blocking mAbs, including LM609 and AP-2, recognize site B5. These results suggest that site B5 is close to or within the putative ligand binding pocket. Since the noninhibitory mAb D57 recognizes site B5, it is not certain whether site B5 is directly related to ligand binding. Site B5 is located in the large predicted loop protruding from the global structure (Fig. 5). Thus it is possible that antibodies access this loop from different directions or change conformation of the predicted loop in different ways. However, we need more definitive structure of the domain to test these possibilities.

The predicted loop region containing Asn-215, Asp-217, and Glu-220 is critical for the binding of ligand-mimetic mAbs or ligands (21). We did not use human-to-mouse mutagenesis to study whether this region overlaps with the binding sites for ligand-mimetic mAbs, because this region is highly conserved between human and mouse  $\beta_3$ . The present results are useful for evaluating two folding models of the putative I-domain-like structure of the  $\beta_3$  subunit (21, 23). The present findings (that sites B3, B5, and B6 are located close to each other on the ligand binding side of the  $\beta_3$  subunit) are consistent with the model by Tuckwell *et al.* (23) (Fig. 5). In this model, the putative RGD binding site (close to site B3) and the predicted loop that is critical for ligand specificity (site B6) are surrounded by conserved oxygenated residues that are critical for binding to ligands and ligand-mimetic mAbs in the  $\beta_3$  subunit (Asp-119, Ser-121, Ser-123, Asp-217, and Glu-220). Consistently, these conserved residues are critical for binding to OPG2/PAC-1 (19, 21, 49). In the model by Tozer *et al.* (21), site B6 is in the apparently nonligand binding site of the domain, indicating that this model does not fit in with the present mapping results.

**Localization of the Binding Sites for Ligand-mimetic mAbs and Ligands at the  $\alpha/\beta$  Boundary**—Fig. 5b is a model of the  $\alpha_{IIb}\beta_3$  globular domain in which the proposed  $\beta$ -propeller domain and the putative I-domain are associated. The regions critical for the binding of ligand-mimetic mAbs and ligands are all in the upper face of both subunits. Interestingly, these results directly demonstrate that the predicted loop at the boundary between repeats 2 and 3 (containing sites A16 and A23) in the proposed  $\beta$ -propeller domain faces the metal ion-dependent adhesive site (MIDAS) region of the putative  $\beta_3$  I-domain (containing sites B3 and B6) in the quaternary structure (Fig. 5). These results predict that these binding sites for ligand-mimetic mAbs and native ligands constitute a ligand binding pocket at the  $\alpha/\beta$  boundary. The positions of binding sites A9, A16, B3, B5, or B6 in this model are consistent with the function-blocking activity of several nonligand-mimetic mAbs (e.g. 7E3, LJ-P9). It is somewhat surprising that the binding of mAbs that are known to be complex-specific can be completely inhibited by substitutions in single subunits. One possibility is that one subunit is involved in antibody specificity by regulating the accessibility to the epitope region.

In summary, we have established that ligand-mimetic antibodies bind to several discontinuous sites in both  $\alpha_{IIb}$  and  $\beta_3$  subunits. It is likely that this unique binding property is related to their ligand-mimetic property (cation and activation dependence). These binding sites are close to or overlapping

with residues/regions that are critical for ligand binding, suggesting that native ligands (e.g. fibrinogen) make direct contact with these discontinuous binding sites in both subunits. These results are consistent with the previous assumption that ligand-mimetic mAbs may have structural and functional similarities to native ligands. It would be interesting to study whether the present model of  $\alpha_{IIb}\beta_3$  may be applicable to other non-I domain integrins.

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